Universidad
Carlos III de Madrid

Departamento de Ingeniería Térmica y de Fluidos

PROYECTO FIN DE CARRERA

Study of a Phase Change Material integrated in a building wall: Experiments and Modelling

Autor: Ana López-Terradas Mota

Tutor: Celia Sobrino Fernández

Leganés, Julio de 2015

Título: Study of a Phase Change Material integrated in a building wall: Experiments and Modelling
Autor: Ana López-Terradas Mota
Director: Celia Sobrino Fernández

EL TRIBUNAL

Presidente: ________________________________

Vocal: ________________________________

Secretario: ________________________________

Realizado el acto de defensa y lectura del Proyecto Fin de Carrera el día __ de _______ de 20__ en Leganés, en la Escuela Politécnica Superior de la Universidad Carlos III de Madrid, acuerda otorgarle la CALIFICACIÓN de

VOCAL

SECRETARIO PRESIDENTE

Acknowledgments

I would like to thank Professor Andreas Athienitis for giving me the opportunity to learn so much about building integrated thermal systems during my stay at Concordia University of Montreal in summer 2014.

To my tutor Vasken Dermardiros who taught me everything I know about Phase Change Materials and guided me throughout the duration of the project, and to everybody else from the Solar Laboratory at Concordia University of Montreal.

To my host university Concordia University of Montreal for accepting me first as an exchange student and afterwards as a research student and for letting me use its impressive facilities.

To my home university Universidad Carlos III de Madrid and all its professors for giving me an excellent education.

Finally, I would like to give thanks to my project mentor in Spain Celia Sobrino for orienting me from beginning to end and giving me useful advice.

Abstract

This thesis studies the behaviour of a phase change material that has been integrated in a building wall for heat storage and thermal comfort purposes. The phase change material, manufactured as thin, almost squared panels, is tested in a controlled environment under certain thermal conditions. Several layers of panels of this material are embedded on the interior of a wall of a small test wooden room.

The material is first heated and then left to cool down in order to observe its performance before, during and after its phase change. In other words, to observe its transition from solid to liquid and then back to solid. The temperature at every layer is recorded at short intervals for the duration of the experiment and this temperature profile is later plotted against time for a neat analysis of the panels. A finite difference model is developed to predict the material behaviour, and the relevance of the most important model parameters is briefly explained. The model is compared to the experimental data and the fit of the model is discussed.

Results show that the material behaves differently when warming up than when cooling down. The freezing point is slightly lower than the melting one. The model reasonably fits the data although it is better at predicting the warming phase.

Keywords

PCM, phase change material, latent heat, heat capacity, passive building design, light-weight building, thermal energy storage, thermal comfort, modeling.

Resumen

Este proyecto estudia el comportamiento de un material de cambio de fase integrado en una pared de un inmueble por razones de almacenamiento de calor y confort térmico. El material de cambio de fase, fabricado en forma de paneles finos casi cuadrados, se prueba en un ambiente controlado bajo ciertas condiciones térmicas. Varias capas de paneles de material se integran en el interior de una pared de una pequeña habitación experimental de madera.

El material se calienta primeramente y más tarde se deja enfriar a fin de observar su comportamiento antes, durante y después de su cambio de fase. En otras palabras, a fin de observar su transición de sólido a líquido y viceversa. La temperatura en cada capa se registra cada poco tiempo para después representar este perfil de temperaturas a lo largo del tiempo y poder hacer un análisis ordenado. Se crea un modelo de diferencias finitas para predecir el comportamiento del material, y se comenta brevemente la relevancia de los parámetros más importantes que intervienen en el modelo. El modelo se compara con los datos experimentales y se analiza su validez y ajuste con estos últimos.

Los resultados muestran que el material se comporta de manera distinta dependiendo de si éste se está calentando o enfriando. El punto de congelación se sitúa ligeramente por debajo del de fusión. El modelo se ajusta razonablemente a los datos, aunque resulta mejor para predecir la fase de calentamiento.

Palabras clave:

MCF, PCM, material de cambio de fase, capacidad calorífica, diseño pasivo de edificios, edificios ligeros, almacenamiento de energía térmica, confort térmico, modelado.

Contents

List of Figures

List of Tables

List of Equations

Nomenclature

T	Node temperature
i	Node being modeled
i+1	Adjacent node to interior of construction
i-1	Adjacent node to exterior of construction
j	Time step
j+1	Next time step
Δt	Calculation time step
Δx	Finite difference layer thickness
cp	Panel specific heat capacity
Kw	Thermal conductivity for interface between i node and $\mathrm{i}+1$ (‘West’ conductivity)
Ke	Thermal conductivity for interface between i node and $\mathrm{i}-1$ (‘East’ conductivity)
ρ	Panel density
$\mathrm{h}_{\mathrm{int}}$	Convective heat transfer coefficient inside the room
$\hat{y}_t$	Predicted (experimental) values
y_t	Model values
n	Number of predictions

Chapter 1

Introduction & Objectives

1.1 Introduction

The experiment described in this thesis took place at Concordia University of Montreal, Canada, at the Centre for Zero Energy Building Studies (CZEBS). This Center aims at reducing the environmental impact of buildings and advancing knowledge through research. To achieve this, many experiments are carried out at their unique facilities. This project describes one experiment from a set of experiments supported by NSERC/Hydro-Québec that focus on lightweight building design. The ultimate goal of these trials is to develop simplified control-oriented models to effectively predict the future response of the buildings [1].

Lightweight constructions are becoming increasingly common in the recent years and can be found in all types of climates such as the very cold Canada or Scandinavia to the very hot tropical climates of South-East Asia. Lightweight buildings are faster and cheaper to produce than heavyweight buildings and are also strong enough from a structural point of view. On the other hand, lightweight constructions have low thermal mass and are therefore unable to store as much heat as heavier buildings in walls and other surfaces. Due to this low thermal storage potential, they tend to suffer large temperature fluctuations which reduce the thermal comfort inside the building. These types of buildings are more dependent on heating or cooling systems thus increasing both energy consumption and CO_2 emissions into the environment [2].

Including phase change materials (from now on, PCMs) in the walls can reduce at the same time these temperature fluctuations and the energy consumed to power HVAC systems. PCMs can be also be smartly used as heat storage elements that absorb heat from a warm room and release it to the same room when this one becomes cold, smoothing out peaks on energy demand [3].

1.2 Objectives

The main objective of this study is to analyze the behaviour of a certain PCM that is used in passive building design in order to provide comfortable room temperatures and minimize temperature peaks for lightweight buildings. The PCM is embedded inside the wall of a small room and tested in a laboratory under controlled conditions. The information provided by the experiment is first analyzed and later used to develop a mathematical model for the material.

Based on this main objective, the following partial objectives are proposed:

- **Subobjetive 1**
  Understand the behaviour of the PCM by analyzing the data obtained experimentally.

- **Subobjetive 2**
  Develop a valid model that predicts said behaviour.

- **Subobjetive 3**
  Analyze how well the model fits the data.

1.3 Means employed

The experiment was carried out at the 'Solar Simulator-Environmental Chamber' in Concordia University of Montreal. This laboratory is 'an internationally unique facility that enables accurate and repeatable testing of solar systems and advanced building envelopes under standard test conditions with full simulated sun and/or indoor plus outdoor conditions. The environmental chamber can test temperatures from -40ºC to 50ºC, under specific conditions, with a temperature stability of 1ºC'[4].

The PCM commercial name is *Energain® thermal mass panel* [5] and is manufactured by E. I. du Pont de Nemours and Company (commonly known as *DuPont*). Its properties are described in Chapter 3.

1.4 Structure of the study

To facilitate the reading of this project, a brief summary of each chapter is included here:

- **Chapter 2 'Background: State of the Art of Phase Change Materials'** is an introduction of PCM technology, description of PCMs special properties and their applications.
- **Chapter 3 'Experiment description'** firstly describes the specific PCM that was used in the experiment and afterwards the experiment itself: what, how, when and where it was done.
- **Chapter 4 'Heat transfer model'** explains the model that is developed to fit the data obtained in the experiment, and comments the different parameters that intervene in the model.
- **Chapter 5 'Results'** discusses and compares the experimental data and the model.
- **Chapter 6 'Conclusions and further work'** closes the study and gives ideas for the future.
- **Chapter 7 'Budget'** is an approximate cost breakdown.
- **Chapter 8 'References'**, self-explanatory.
- **Chapter 9 'Annexes'** includes extra information about the panels and the model.

Chapter 2

Background: State of the art of Phase Change Materials

2.1 Introduction to Phase Change Materials

Phase change materials (PCMs) are substances capable of storing and releasing large amounts of energy when they change phase. In a phase change, the temperature remains constant so the energy absorbed or released is called *latent heat*. On PCMs, this phase transition is usually the solid-liquid one, also called 'fusion', and so the PCM typically possess high latent heat *of fusion*.

It is important to clarify that PCMs also store heat at temperatures far from a phase change in the form of *sensible heat* as their temperature rises, as any other substance. However, PCMs' sensible heat storage is much less relevant than latent heat storage and usually a great interval of temperatures is required for the sensible heat to play an important role. Figure 1 gives a rough idea of how heat is stored in a PCM.

PCMs are therefore interesting to use in a range of temperatures that cover the solid-liquid phase change, and so it is very important to choose the PCM accordingly. Ideally, PCMs change phase at a specific temperature. In practice, only ultra-pure paraffins are this accurate [7] and the majority of PCM change phase on a small temperature range.

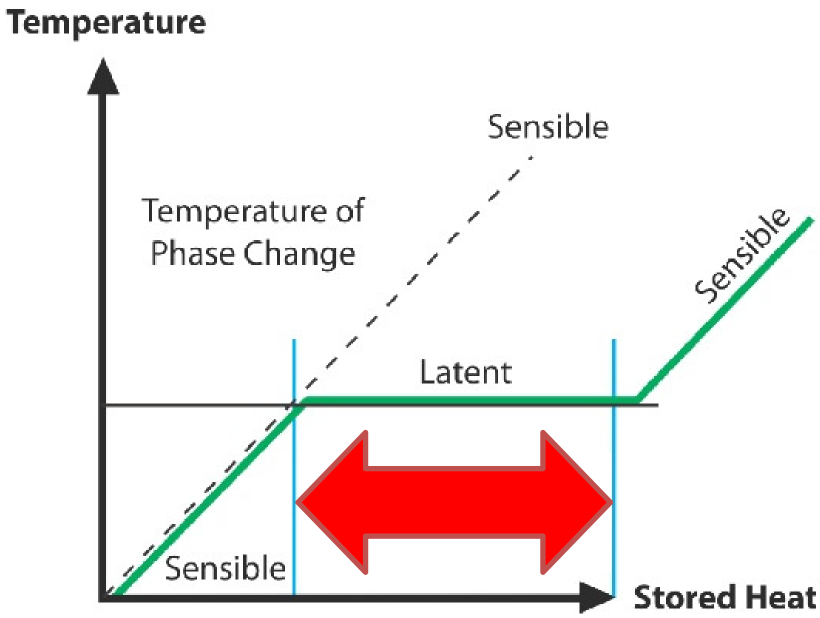

Figure 1. Temperature vs Heat: Latent and sensible [6]

Because of their interesting properties, PCMs are used for energy-saving and thermal energy storage purposes. Building design is a big application field where this technology can be efficiently used. In particular, PCMs are used as elements on the design of *Passive solar buildings* [8].

2.1.1 PCM Applications in Passive Solar Building Design

Passive solar building design refers to the use of the sun's energy for heating and cooling living spaces without active mechanical systems (such as fans). In passive buildings, walls, windows, ceilings and floors can collect or reject energy from the rooms to provide thermal comfort.

In order for a material to effectively absorb and store energy, it should have high thermal mass. Traditionally, for structural reasons, houses were made of heavy construction materials such as concrete, brick or stone, so the high density of these materials enabled them to store heat, providing 'thermal inertia' against temperature fluctuations. In the recent times however, as construction technologies improve, lightweight materials such as timber (engineered wood) are becoming very common especially in industrialized countries [9]. Wood is cheap, relatively fast to produce, flexible under loads and very strong when compressed vertically, so it makes a reasonably good construction material. However, wooden houses are much lighter than traditional ones, i.e. they have much less thermal mass and so they heat up and cool down much faster, which translates into higher room temperatures during the day and lower room temperatures at night.

There are two main problems with this greater temperature oscillation:

- Lightweight buildings reach faster than heavyweight ones unpleasant high temperatures and/or uncomfortable low temperatures.
- More money and energy has to be wasted on HVAC systems to overcome this concern.

These are two problems that can be eased by adding PCM on walls, ceilings or floors. Below is a brief explanation how this is done.

2.1.2 How PCMs work

The human body is extremely sensitive to temperature changes and has a very small temperature interval where it feels neither too warm nor too cold. Figure 2 depicts this small gap for an average person in a summer climate and states a temperature interval of only 4ºC for human comfort indoors: from 22ºC to 26ºC [7]:

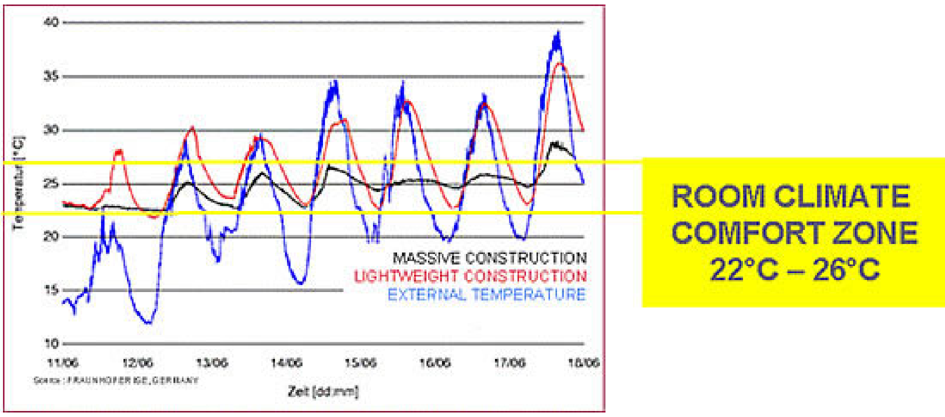

Figure 2. Room climate vs Thermal mass [7]

Here is where a PCM becomes useful. Let's imagine a summer day: The sun slowly starts heating up a room. When the room and its walls reach a certain temperature, the PCM inside the walls starts melting. Because the PCM needs some external energy to go from solid to liquid, it takes heat from the surroundings, in this case the room as we see in Figure 3. PCM panels are designed in such a way that their melting temperature is about the same temperature at which the human body starts feeling uncomfortably hot (around 26ºC according to Figure 2.

As the PCM absorbs heat, the room is actually cooling down. In practice, the PCM panels take some time to finish the phase change and meanwhile the room is receiving heat itself from the sun. The room temperature will then ideally remain inside the comfort zone until night. Of course, the panels can only store a limited amount of latent heat and after they have completely melted they do not store as much energy so it is very important to effectively calculate in advance, based on the irradiation the room receives, the amount of PCM required for such room.

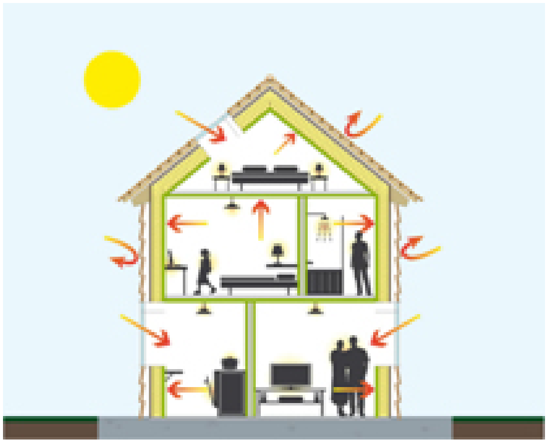

Figure 3. Day time: PCM absorbs heat [6]

Figure 4. Night time: PCM releases heat [6]

At night, or when the room begins to cool down, the PCM goes through its phase change again, only now it goes from liquid to solid. As it solidifies, it releases heat into the room, warming it up (Figure 4). Note that now the ideal temperature for the PCM to solidify would be 22ºC (lower limit of the comfort zone according to Figure 2. However, it is difficult to create a phase change material on purpose that would melt at a certain temperature and then solidify around 4ºC below. Often PCMs suffer hysteresis (different behaviour when melting than when freezing or/and subcooling (solidifying at a lower temperature than the melting one). But these effects are usually undesirable because they make PCMs much more difficult to model [10].

Figure 2 also shows the temperature oscillations for lightweight and heavy construction buildings for a typical summer week on a warm climate. Indoor temperature inside heavy construction buildings usually falls inside the comfort room temperature interval. Lightweight buildings, in the other hand, exceed the upper limit easily every day.

In another graph, Figure 5, one can also notice the difference in room temperature over the course of a day. This figure shows the difference in room air temperature among rooms with different internal construction elements severely exposed to solar radiation in summer. The interrupted line corresponds to rooms of lightweight construction with optimized solar protection. It is easy to observe that there is a big difference on indoors air temperature, up to 12 K, between the lightweight and the heavyweight building [11]. The lightweight building is therefore much more dependent on heating and cooling devices, which results in a higher money and energy waste in/by these devices, and an increase in CO_2 emissions. This temperature difference could be eliminated, or at least reduced, by using elements that would increase the thermal mass of the building, such as PCMs.

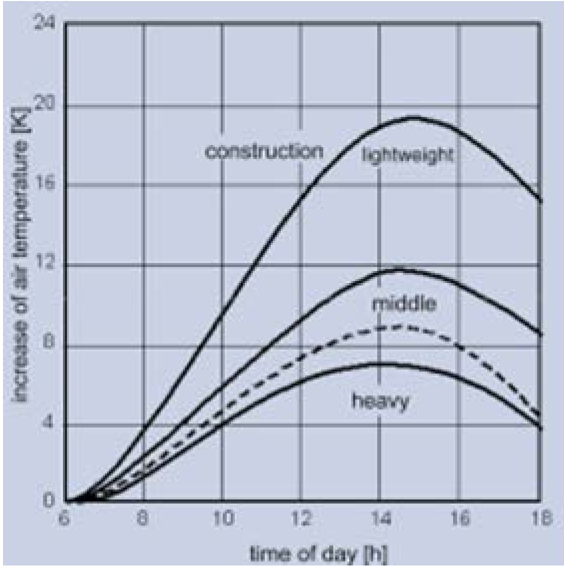

Figure 5. Increase of air temperature [11]

2.2 Important properties

Below in Table 1 is a series of desired properties in a PCM. It is nearly impossible for a given PCM to have all these properties, so usually two or more different types of PCMs are combined (See *Section 2.3 Types of PCMs*).

Thermal Properties	Chemical properties	Physical properties	Economic Properties
Phase change temperature fitted to application	Stability	Low density variation	Cheap
High change of enthalpy near temperature of use	No phase separation	High density	Abundant
High thermal conductivity in both solid and liquid phases	Compatibility with container materials	Small or no sub cooling	
	Non-toxic, non-flammable, non-polluting		

Table 1. PCM desired properties [12]

2.3 Types of PCMs

2.3.1 Types of PCM based on the phase change they use to store heat

Although most of PCMs used nowadays are liquid-solid PCMs for practical reasons, PCMs can store latent heat through any phase change:

- **Solid-solid:** typically very slow and/or with low heat capacity, but in recent years there has been some development on this type of PCMs and some of them have latent heat values comparable to solid-liquid PCMs [13].
- **Solid-liquid**: **the vast majority of PCMs:** high latent heat and usually high conductivity.
- **Solid-gas and liquid-gas:** not useful for most of the applications because they require large volumes or high pressures when in gas phase.

2.3.2 Types of PCM based on their structure

Solid-liquid PCMs can be further divided into three main groups, depending on their compound structure [12]:

- **Organics:** Paraffins and fatty acids. Paraffins are widely used because, compared to other PCMs, they have wide and variable melting point range and relatively high heat capacity. On the other hand, they have low thermal conductivity (around 0.2 W/mK), a relatively large volume change and they are flammable.
- **Inorganics:** Metallics and salt hydrates, the latter being much more common. Salt hydrates have high heat capacity and high thermal conductivity (around 0.5 W/mK). As major disadvantage, they have low stability and a large volume change.
- **Eutectics:** Eutectics are mixtures of two or more compounds, organic, inorganic or organic-inorganic. This type of PCM is very interesting because it can combine the advantages of organics and inorganics or reduce the disadvantages of them. For example, an organic paraffin can be mixed with an inorganic salt with large conductivity to obtain an improved material. The main limitation of eutectics is the lack of data as they are very new in the market and have yet to be tested.

Figure 6 represents this classification:

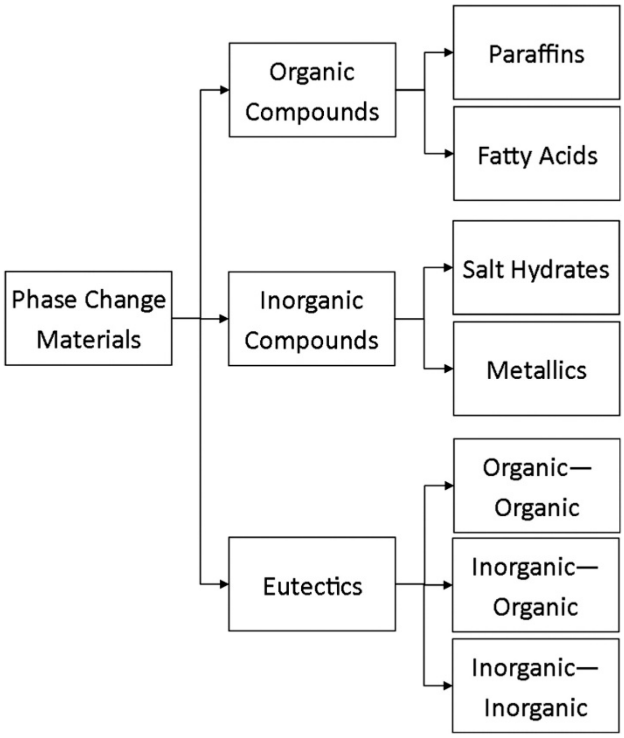

Figure 6. Types of PCMs depending of their structure [12]

For building design, salt hydrates and paraffins, or mixtures of these two are normally used as they are the only ones that cover the range of temperatures of human comfort as seen in Figure 7:

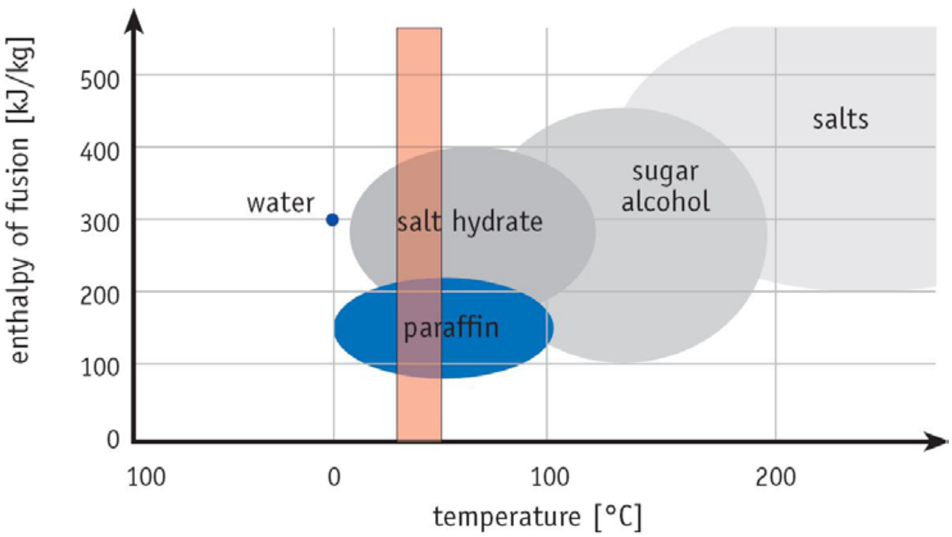

Figure 7. Range of action of different PCM technologies [12]

2.4 Advantages & Disadvantages of PCM use in building design

Below is a brief list of the main advantages and disadvantages of PCMs in relation to building design [14]:

2.4.1 Advantages

- **Increases room comfort:** Less temperature oscillation.
- **Money and energy savings:** Reduces the need for heating and air conditioning.
- **Shifts peak energy demand:** PCMs can store energy at off-peak time and release it during peak periods [15].
- **Increases energy control:** Because PCMs moderate temperature oscillations, the building becomes less dependent on weather conditions.
- **Passive element:** It does not require active cooling/heating, it is not difficult to install and requires little maintenance.
- **Decreases CO_2 emissions:** Less electricity consumption translates into less CO_2 emitted to the atmosphere.

2.4.2 Disadvantages

- **High initial investment:** PCMs are expensive compared to other construction materials.
- **Limited experience:** Most of PCMs are relatively new technology and more research is needed for an effective temperature control.
- **Flammability:** Some of the PCMs, especially organic ones, can represent a serious fire hazard. Normally these types of PCMs are mixed with other non-flammable PCM compounds and fire retardants to eliminate this hazard.

2.5 Other applications

As well as building design, PCMs have many other fields of applications for thermal energy storage or thermal protection and comfort. Some of the most interesting applications are listed below:

- **Medical use:** PCMs are being incorporated with insulating materials in containers to transport and temporary store red blood cells and platelets [16].
- **Solar power plants:** PCMs can be used to store heat during the day and release at night for power generation [17].
- **Textiles used in clothing:** To prevent extreme temperatures on the human body and prevent dehydration and other health problems, PCMs can be included on garments. In particular, firefighters, soldiers and athletes can benefit from such clothing [16].
- **Smoothing exothermic temperature peaks in chemical reactions** [18]: PCMs absorb heat from the reaction [18].
- **Thermal protection of food:** transport, hotel trade, ice-cream, etc. [18].
- **Cooling of food:** e.g. for beverages such as coffee or milk [18].

Chapter 3

Experiment description

3.1 PCM of the experiment

The PCM studied is called *Energain® thermal mass panel* [5] and is manufactured in the shape of panels. The panes are made by E. I. du Pont de Nemours and Company (commonly known as DuPont), an American chemical company that manufactures and develops products in several fields, such as Building & Construction, Transportation or Electronics [19].

3.1.1 Descriptive properties

Each panel measures about 1.2 meter by 1 meter, has an approximate thickness of 5mm (See Figure 8) and weighs around 5.4 kg.

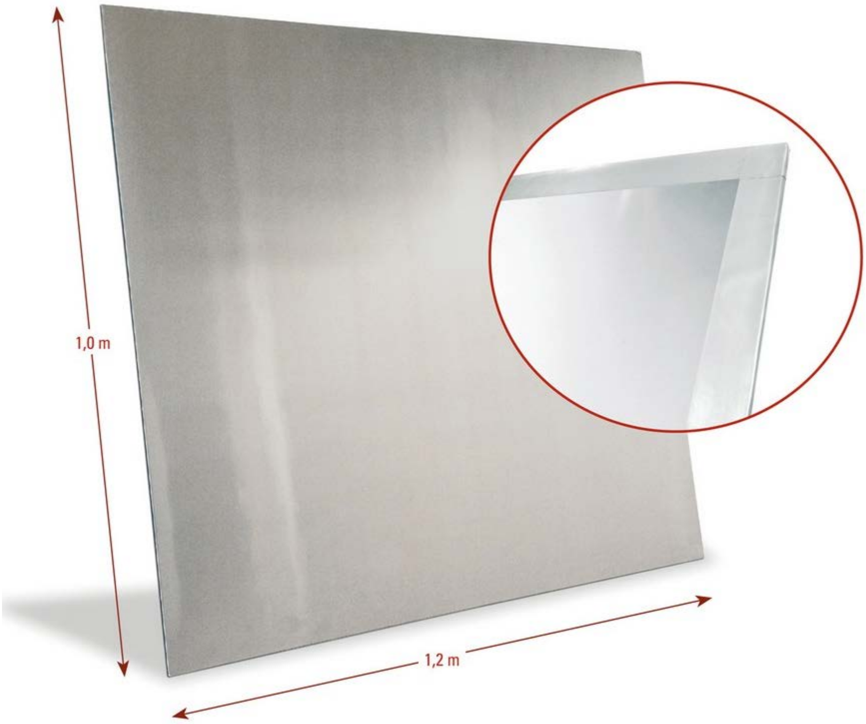

Figure 8. PCM panel [20]

The PCM is actually a mixture of an ethylene based polymer (40%) designed by DuPont and a paraffin wax (60%) laminated on both sides with a 100 µm aluminum sheet. The panels are taped at the edges with a special aluminum tape made by the same manufacturer. Below are some of the PCM properties given by the manufacturer.

3.1.2 Thermal & Physical properties

We can find most of the relevant thermal & physical properties in the manufacturer website [5] (See Table 2):

Property	Value
Melting point	21.7ºC (DSC method, 1°C/min)
Latent heat storage capacity (0º-30ºC)	>70kJ/kg
Total heat storage capacity (0º-30ºC)	~140 kJ/kg
Conductivity (solid)	0.18 W/mK
Conductivity (liquid)	0.14 W/mK

Table 2. PCM Thermal & Physical properties [5]

The manufacturer does not provide the relationship between the material's heat capacity and its temperature. This relationship was nevertheless found in an article written by Kuznik [3] in which he studied the same material with similar conditions. He measured the PCM heat capacity while heating it and freezing it and plotted the specific heat obtained versus the temperature. Figure 9 shows the relationship between specific heat capacity and temperature:

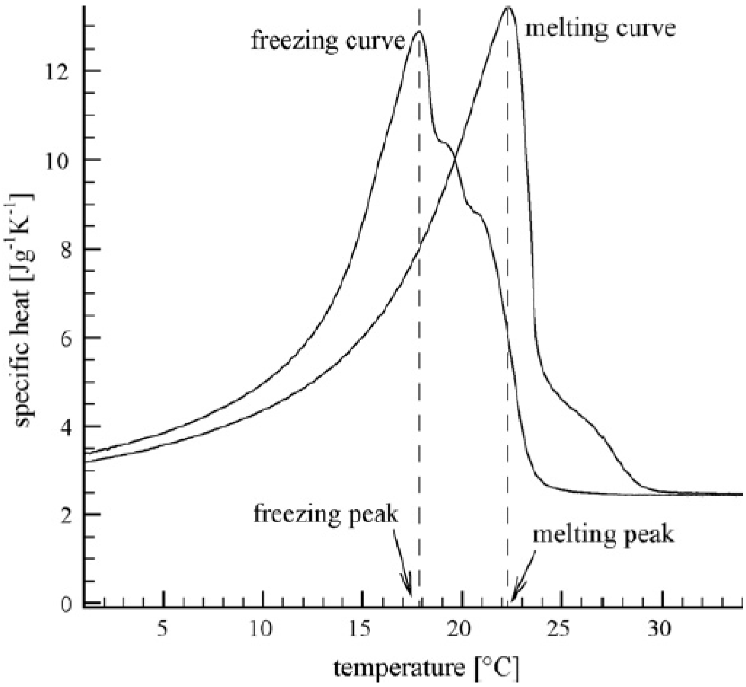

Figure 9. Experimental specific heat of the PCM [3]

So specific heat capacity ranges from about $2500 \frac{J}{kg \cdot K}$ $(liquid)$ to $3300 \frac{J}{kg \cdot K}$ $(solid)$ but drastically increasing to a maximum of $13000 \frac{J}{kg \cdot K}$ approx. around the melting and freezing points.

These properties are furtherly described at *Section 4.2 Determination of variables,* as some of these values may differ slightly from the actual properties observed in the experiment.

3.1.3 Comparison to other construction materials

A real-life experiment made in France in summer by the manufacturer in cooperation with EDF (Electricité de France) tested the panels and showed that room temperature was reduced by 4.5ºC on average and 6.7ºC maximum [5]. (See Figure 10 below):

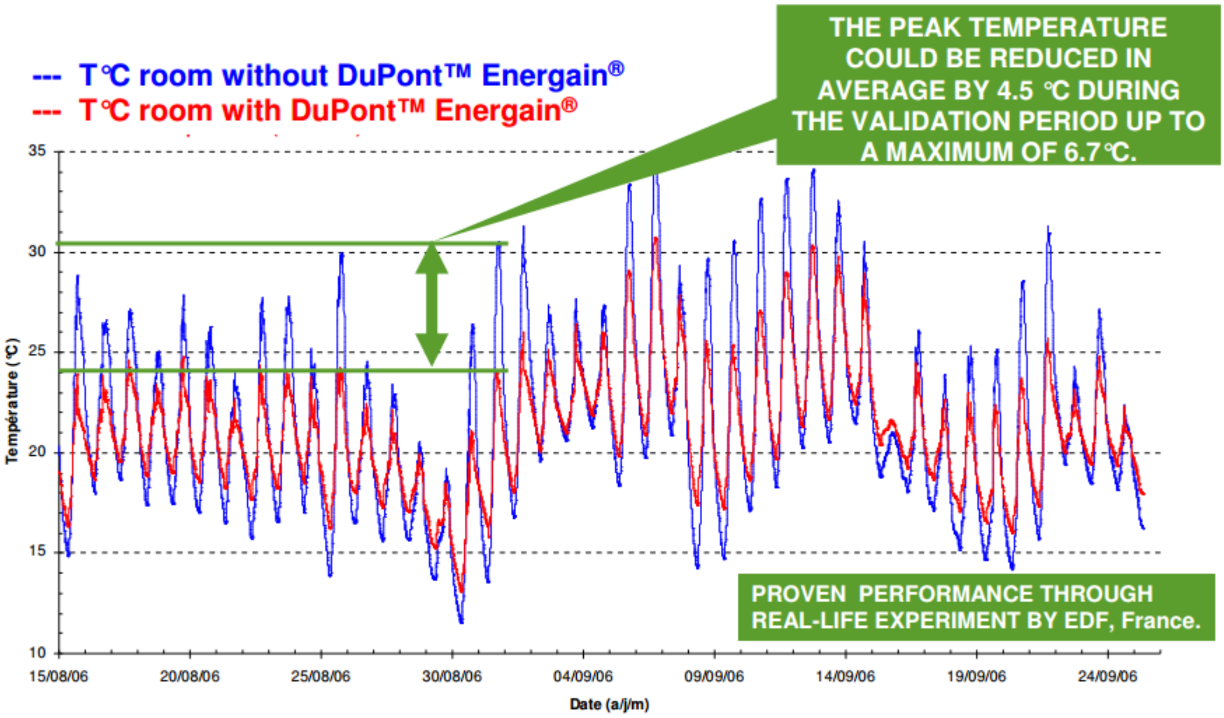

Figure 10. Thermal oscilation with and without the PCM [5]

3.2 Experiment setup

3.2.1 Introduction

The aim of the experiment is to test the PCM under certain conditions of heat input and temperature to observe the material through its phase change, as well as before and after this change. The PCM panels are embedded on the interior of one wall (from now on, 'room wall') of a small room (from now on, 'test room') (Figure 11). The total wall is therefore made of: *a)* the actual PCMs panels and *b)* the room wall. The room is then slowly heated up by a small heater placed inside the room facing said wall. The panels start off as solid material, slowly warm up and liquefy. Afterwards, the panels cool down and turn into a solid state again.

The panels are warmed for about 3000 min (50hours approx), then the heater is turned off and the panels are left to cool for an additional 1000 min (17 hours approx).

3.2.2 Location of experiment

The test room is located inside an environmental chamber. The chamber provides a stable environment in which to test different scenarios depending on temperature and heat input among others. (See *Section 1.3 Means employed*). The temperature in the chamber can be dynamically controlled so that any temperature evolution can be generated [4].

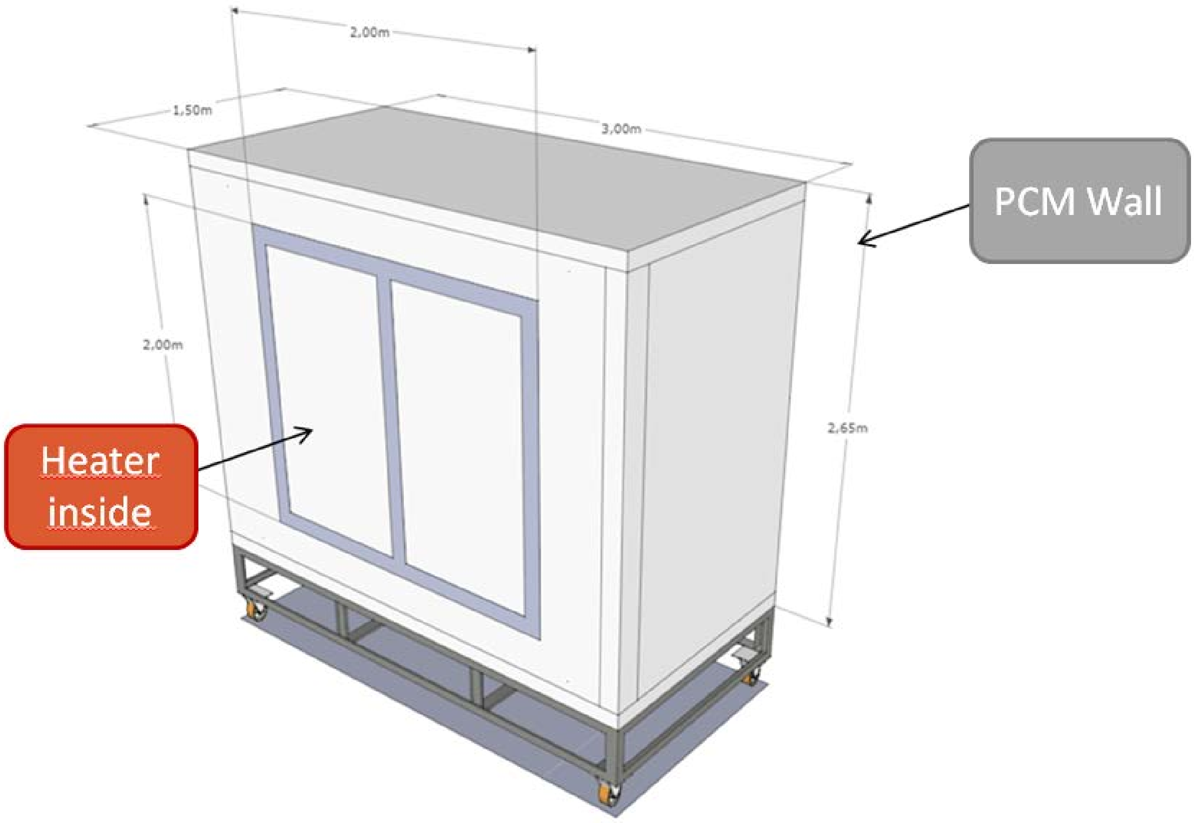

Figure 11. Schematics of the test room [1]

3.2.3 Experiment description

3.2.3.1 Experiment parameters

To keep things simple, both the exterior temperature and the heating input are kept constant. The exterior temperature (the temperature of the environmental chamber) is set at 5ºC. Inside the room, the initial temperature is around 12ºC. A small heater inside the room provides constant power of 350 W. (See Table 3):

Parameter	Value
Interior temperature	From 12°C to 25°C
Exterior temperature (constant)	5°C
Heating source (constant)	350 W

Table 3. Experiment parameters

Ideally, the room would be heated by the sun radiation that goes through a window opposite to the PCM wall. In practice, to simplify the experiment, the heat is provided by the heater inside the room. There is a plenum fan that circulates the air to keep a homogeneous temperature in the room.

The heater warms up the wall very slowly, at a rate of about 0.005 K/min. This rate is so low as to clearly see the phase change, but buildings in summer normally heat up faster, at around 0.01-0.05 K/min [3].

The heater is turned off once the room reaches 25ºC, after the panels experience the phase change (at 21.7ºC according to the manufacturer).

3.2.3.2 Experiment PCM wall description

As previously mentioned, the PCM panels are embedded on the interior of the room wall. (See Figure 12). The room wall is 2.8 m wide by 2.4 m high. Four PCM panels are put together, 2 above and 2 below, to cover around 80% of the room wall's inner surface.

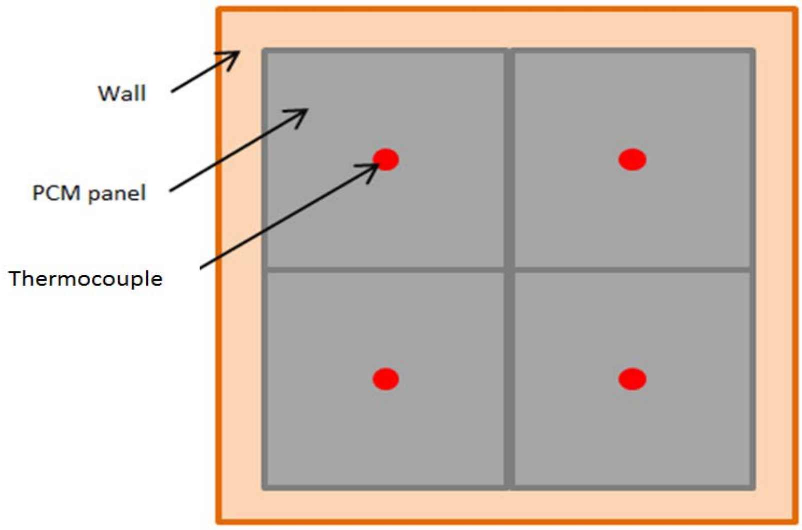

Figure 12. PCM wall schematics-front view

There are 5 layers of 4 panels each (See Figure 13). All 5 layers are pressed together so as to increase heat transfer between them. The temperature of every panel is being measured every 15 seconds by a thermocouple located in the middle of the surface of the panel. Every 3 min, the average of these temperatures is recorded.

Because there are 5 layers of PCM together, there are actually 6 surfaces that are being measured. Each of these surfaces is referred with a letter, starting from H (interior layer, closest layer to the room) to A (exterior layer, furthest layer from the room). The warm air is being recirculated inside the room and there is no noticeable stack effect so the temperature on the upper panels is similar to the temperature of the lower panels at any time. For practical reasons, only one of the four set of panels is analyzed.

The Room Wall is about 12 cm thick and is made of two layers of plywood (1 cm and 2 cm) and a 9 m-thick fiberglass layer in between these two. Fiberglass has a very low conductivity (about 0.04 W/mK) and makes a good insulator. The U-value of the total wall was calculated: about U_{PCM}=0.37 W/m^{2}K and for the total room U_{ROOM}=0.56 W/m^{2}K

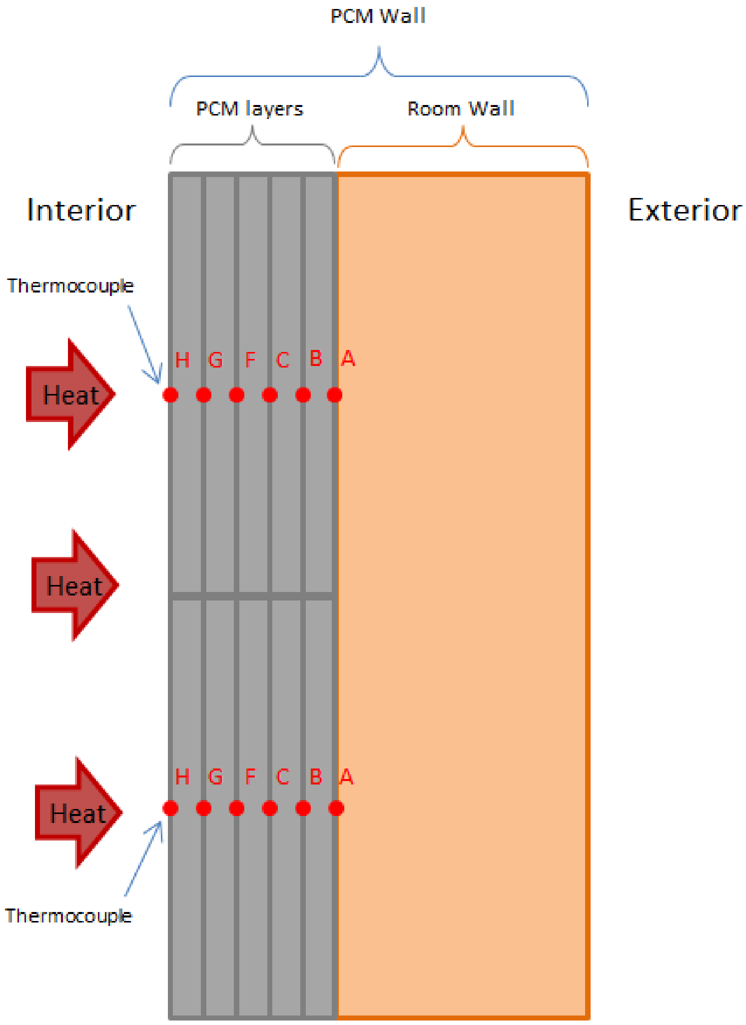

Figure 13. PCM wall schematics-lateral view

Chapter 4

Heat transfer model

4.1 Model description

To predict the temperature evolution of the PCM layers a model is developed. An implicit finite-difference method is used based on a model from EnergyPlus called *Conduction Finite Difference Solution Algorithm* [21]. The software MATLAB is used for the model; the code for the model can be found in *Section 9.2 Annex II.*

Conceptually, we can calculate the heat transfer by making the stored heat of a panel equal to the heat that enters said panel minus the heat that exits it. The mathematical expression for an internal node N is the following:

$$\rho Cp\Delta x \frac{\left(T_i^{j+1} - T_i^j\right)}{\Delta t} = k_W \frac{\left(T_{i+1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_E \frac{\left(T_{i-1}^{j+1} - T_i^{j+1}\right)}{\Delta x}$$

Equation 1. Conduction Finite difference solution algorithm [21]

Where

T	Node temperature
i	Node being modeled
i+1	Adjacent node to **interior** of construction
i-1	Adjacent node to **exterior** of construction
j	Time step
j+1	Next time step
Δt	Calculation time step
Δx	Finite difference layer thickness
Cp	Panel specific heat capacity
Kw	Thermal conductivity for interface between i node and $\mathrm{i}+1$ ('West' conductivity)
Ke	Thermal conductivity for interface between i node and $\mathrm{i}-1$ ('East' conductivity)
ρ	Panel density

The first node H is modeled different as it is receiving heat from the room by convection.

The temperature is being measured on the surface of each of the panels so the nodes are the surfaces of the panels, 6 surfaces in total for 5 panels (H, G, F, C, B, A from the interior to the exterior).

The finite difference layer thickness is considered to be about the PCM actual thickness for all the panels except the first and last one; for these ones the finite difference layer thickness is half the PCM thickness. (See Figure 14):

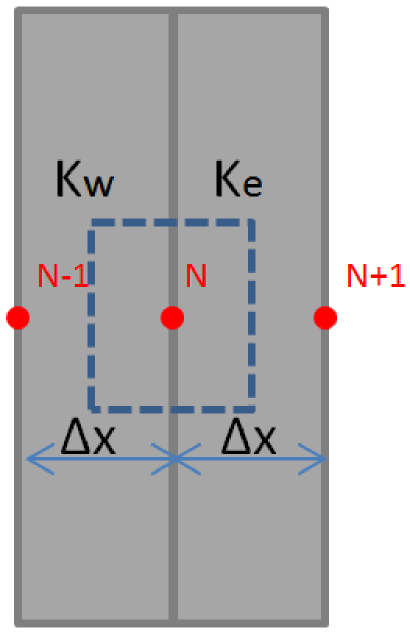

Figure 14. PCM finite difference nodes schematics

The calculation time step (Δt) is three minutes (180s) because the temperatures are averaged every three minutes during the experiment.

4.1.1 Assumptions for the model

For each panel, the conduction heat transfer is assumed to be unidirectional.

The room wall that separates the panels from the exterior is reasonably well insulated. It is considered that the most exterior PCM panel is externally adiabatic.

Radiation heat transfer to or from the wall is not considered.

On the first and last nodes the finite difference layer thickness is half of the other layers' thickness.

4.1.2 Model equations

The equations for the six nodes are therefore the following:

$$
\begin{aligned}
&\text{A: } \alpha * \left(T_A^{j+1} - T_A^{j}\right) = 0 + \gamma\left(T_B^{j+1} - T_A^{j+1}\right)\\
&\text{B: } \alpha\left(T_B^{j+1} - T_B^{j}\right) = \beta\left(T_A^{j+1} - T_B^{j+1}\right) + \gamma\left(T_C^{j+1} - T_B^{j+1}\right)\\
&\text{C: } \alpha\left(T_C^{j+1} - T_C^{j}\right) = \beta\left(T_B^{j+1} - T_C^{j+1}\right) + \gamma\left(T_F^{j+1} - T_C^{j+1}\right)\\
&\text{F: } \alpha\left(T_F^{j+1} - T_F^{j}\right) = \beta\left(T_C^{j+1} - T_F^{j+1}\right) + \gamma\left(T_G^{j+1} - T_F^{j+1}\right)\\
&\text{G: } \alpha\left(T_G^{j+1} - T_G^{j}\right) = \beta\left(T_F^{j+1} - T_G^{j+1}\right) + \gamma\left(T_H^{j+1} - T_G^{j+1}\right)\\
&\text{H:} \alpha * \left(T_H^{j+1} - T_H^{j}\right) = \beta\left(T_G^{j+1} - T_H^{j+1}\right) + h_{int}\left(T_{int}^{j+1} - T_H^{j+1}\right)
\end{aligned}
$$

Equation 2. Nodal model equations

Where

$$\alpha = \frac{\rho * cp * \Delta x}{\Delta t}$$
$$\beta = \frac{Ke}{\Delta x}$$
$$\gamma = \frac{Kw}{\Delta x}$$

h_{int} is the convective heat transfer coefficient inside the room and T_{int} is the inside air temperature 50 mm away from the interior panel (H).

As boundary conditions we know T_{int} so we can calculate h_{int} at any time.

4.2 Determination of variables

A model should be made as simple as possible, but there are several variables that depend on temperature and therefore change at every time step, for every layer. PCMs can be challenging to model because sometimes it is not possible to assume a constant value for some variables, mostly because the PCM characteristics can change a lot when changing phase. Here are the panel or air characteristics present in the model that vary with temperature:

- PCM thermal conductivity $k(T)$
- PCM density $\rho(T)$
- PCM Heat capacity $cp(T)$
- Air convection coefficient $h_{int}(T)$

Providing they do not change too much, some of these variables will be kept constant. These values considered constant are firstly used to initiate the model and later analyzed and commented in *Section 5.2 Analysis of the model.*

4.2.1 Heat capacity

Heat capacity in particular varies greatly within a small temperature interval and it is necessary to take into account this variation. As previously stated in chapter 3, heat capacity is taken from a research article by Kuznik [3]. Figure 15 shows the relationship between specific heat capacity and temperature:

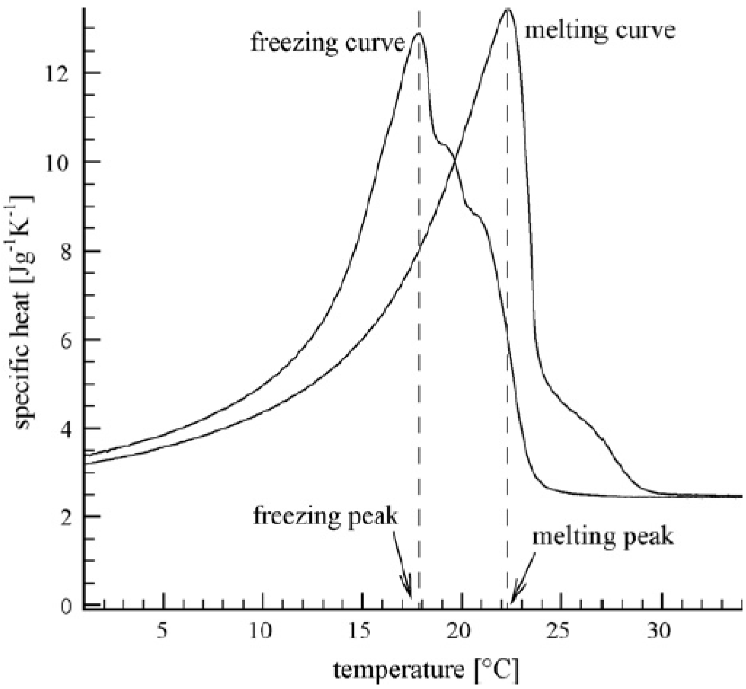

Figure 15. Experimental specific heat of the PCM [3]

It is easy to observe just how rapidly the capacity grows when it becomes closer to its peaks (melting and freezing points). Peak freezing temperature is around 17.8CºC, while peak melting temperature is about 22.3ºC, almost 5 degrees higher. Note that the manufacturer only states one phase change point (melting) measured at 21.7ºC. The fact that there are two different curves for the same material depending on whether it is warming up or cooling down indicates that the material is subjected to hysteresis, i.e. the same material has different behaviour when cooling down than when warming up. This presents another challenge when modelling the material. We should take into account that the model should work both for the melting and freezing process. In general, PCM freezing process is more complicated to model as they are sometimes subjected to sub cooling [22].

To insert the heat capacity $cp(T)$ as a function of temperature in the model, we don't have the exact Kuznik curves but rather discrete values, so for example $cp(20)$, $cp(20.5)$, $cp(21)$ and so on. (Exact values can be found in *Section 9.2 Annex II).* To obtain a continuous $cp(T)$ curve, we use MATLAB integrated Piecewise Cubic Hermite Interpolating Polynomial (PCHIP).

In the model, every time step the temperature of a layer is compared to the preceding temperature of that layer. If the actual temperature is higher than the previous one, the model takes the melting curve for that specific layer. If the temperature is lower, the model then takes the freezing curve. There might be some cases where the temperature of two consecutive time steps is exactly the same. In this case, for simplicity, the model takes also the melting path.

Kuznik's heat capacity values were obtained with a DSC (differential scanning calorimeter), a standard measurement method based on the detection of differences in the thermal responses that a reference and sample show when simultaneously subjected to a temperature program [23]. Kuznik, for his measurements, used a heating/cooling rate of 0.05K/min (about 3ºC/h), average heating rate in light-weight buildings in summer when solar gains are maximum. It is necessary to point out that the capacities and phase change temperatures obtained by the DSC depend on the rate used and the quantity of mass measured. Tipically, the higher the heating rate, the higher the melting point [23].

In our experiment, the heating rate is about ten times slower than the one used by Kuznik, so the heat capacity curves may not exactly fit into our model, but it is a good approximation. Also, the DSC measures a small, thin piece of the material, much smaller than even one of our layers.

In addition, because the heat capacity varies a lot around the peak values, if the peak values from our panels vary slightly from the theoretical peak values, the $cp(T)$ will be very different from the values obtained by Kuznik.

For all these reasons, our curves may vary from Kuznik's, but they provide a good approximation.

4.2.2 Density and thermal conductivity

The values for these two properties are given by the manufacturer:

PCM density $\rho = 855.5\ kg/m^3$
PCM solid thermal conductivity $k_{\text{solid}} = 0.18\ W/mK$
PCM liquid thermal conductivity $k_{\text{liquid}} = 0.14\ W/mK$

For the moment these will be the values used in the model.

4.2.3 Convective heat transfer coefficient inside the room

Inside the room, natural convection is very low so we need something that will increase the heat transfer. A fan is for this reason installed inside the room to circulate the air and also to make sure the temperature from the top to the bottom is as constant as possible. This fan, running smoothly at around $v = 2\ m/s$, forces convection to the PCM wall. It is difficult to give an accurate value for the convection coefficient due to the conditions of the experiment itself, but an average value can be estimated following ASHRAE's [24] Nusselt number correlation (See Figure 16):

$$\boldsymbol{Nu_x = 0.029 * Re^{4/5} * Pr^{1/3}}$$

Figure 16. Nusselt correlation for forced convection [24]

Where

$$5 * 10^5 < Re < 10^7,$$
$$0.6 < Pr < 60$$

(Assuming turbulent flow, forced convection)

This coefficient depends on temperature, but for the small range of temperature the panels experience it does not vary greatly. For example, for a film temperature $T_f = 20°C$, using Nusselt correlation:

$$h_{int}(20°C) = 8.6\ W/m^2K$$

For $T_f = 25°C$:

$$h_{int}(25°C) = 8.5\ W/m^2K$$

And even for $T_f = 12°C$:

$$h_{int}(12°C) = 8.7\ W/m^2K$$

Which gives an idea of just how little h_{int} varies with temperature at the range the PCM is used. Therefore it is assumed constant and with the value for a film temperature of $T_f = 20°C$:

$$h_{int} = h_{int}(20°C) = 8.6\ W/m^2K$$

To sum up, thermal conductivity, density and air convection coefficient are kept constant while heat capacity is included in the model as a function of temperature. In the next chapter these values properties are tested to see if they are accurate enough.

Chapter 5

Results

5.1 Analysis of experimental data

Here is a brief analysis of how each PCM layer reacted in the experiment.

In Figure 17, the temperatures of each of the panels are plotted against time. Bear in mind the graph plots the temperature on the panels' surfaces so there are six layers in total, being layer H the most interior one and A the most exterior one.

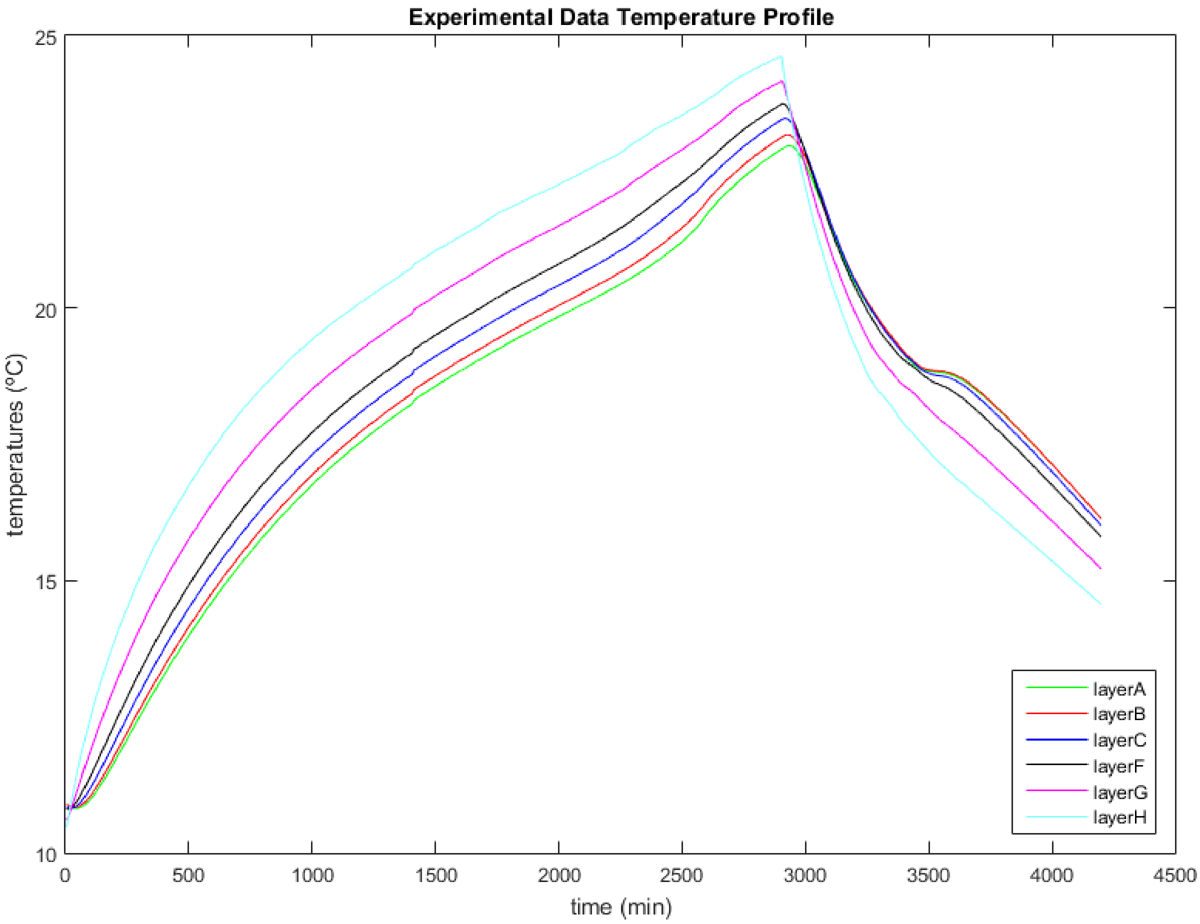

Figure 17. PCM temperature vs time

We can divide the graph into two obvious regions: upward curves (melting) and downward curves (freezing). Within these two regions, we can distinguish some characteristic patterns.

5.1.1 Warming up: Charging of wall

On the first part of the experiment, the room and the panels warm up: the PCM wall is 'charging' (see Figure 18). The solid PCM eventually reaches its melting point and turns into liquid, absorbing latent heat in the process.

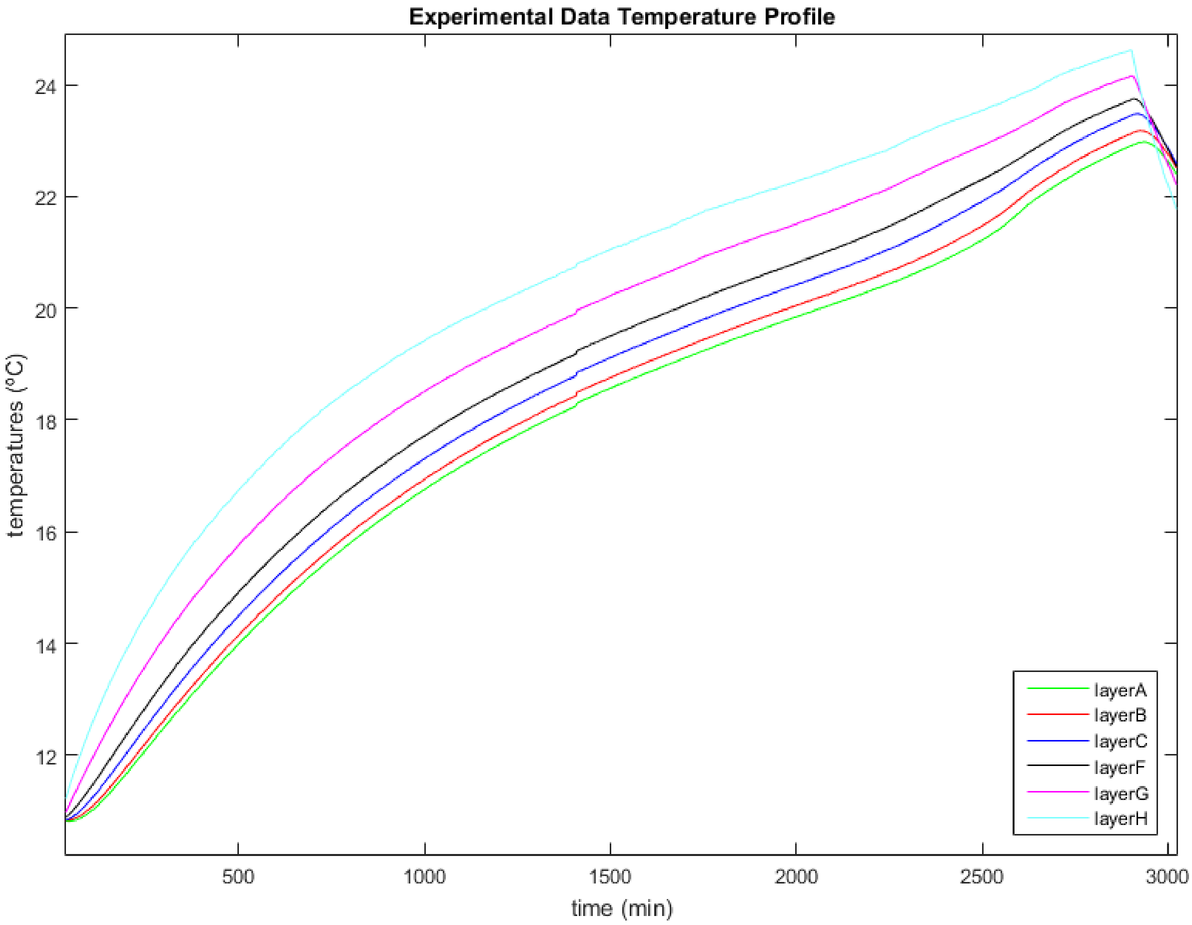

Figure 18. Warming up: Charging of PCM wall

The melting curve (Figure 18) can be further divided into three zones:

From the beginning until around $time = 1000\ min$, where the lines are steep and still close to each other. It is interesting to see how the temperature gap between two consecutive layers for a given time (and the time gap for a given temperature) narrows as we move further from the room. The temperature gap for a given time between layer H and layer G is similar to the gap between layer G and layer F, but about ten times as big as the gap among the last two layers. Basically, every layer needs a time t to reach the temperature of its previous layer, and the further you go from the room, the smaller this additional time t is, because the layers keep getting warmer and warmer with time. This does not indicate that the last layers are warming up faster, as we will soon see.

In the second zone, between around $time = 1000\ min$ and $time = 2500\ min$, the curves 'slow down': They need more time to reach any extra degree. (There is a small glitch on the data at about $time = 1500\ min$ due to a minor technical issue but it is irrelevant for the experiment).

The third region of the melting curve starts at about $time = 2500\ min$, or around 21ºC for layer A. Figure 19 below shows a close-up of this region. A small kink is observed around this temperature, especially in the outer layers. This kink is actually the phase change taking place: the heat capacity suddenly increases before the melting point and quickly drops right after it, increasing the slope of the curves during the phase change. This effect is easier to appreciate in the outer layers, but it happens in every panel to some extent. The first layers warm up a bit faster than the last ones; the first layer reaches a higher temperature than the last one (about 2ºC higher) in roughly the same time interval, which might explain why not all panels reach the melting point the same way and at the same time.

Note that for the last panel the phase change takes place at around 21-22 ºC, but for the first panels the phase change occurs at a slightly higher range, at around 22-23ºC.

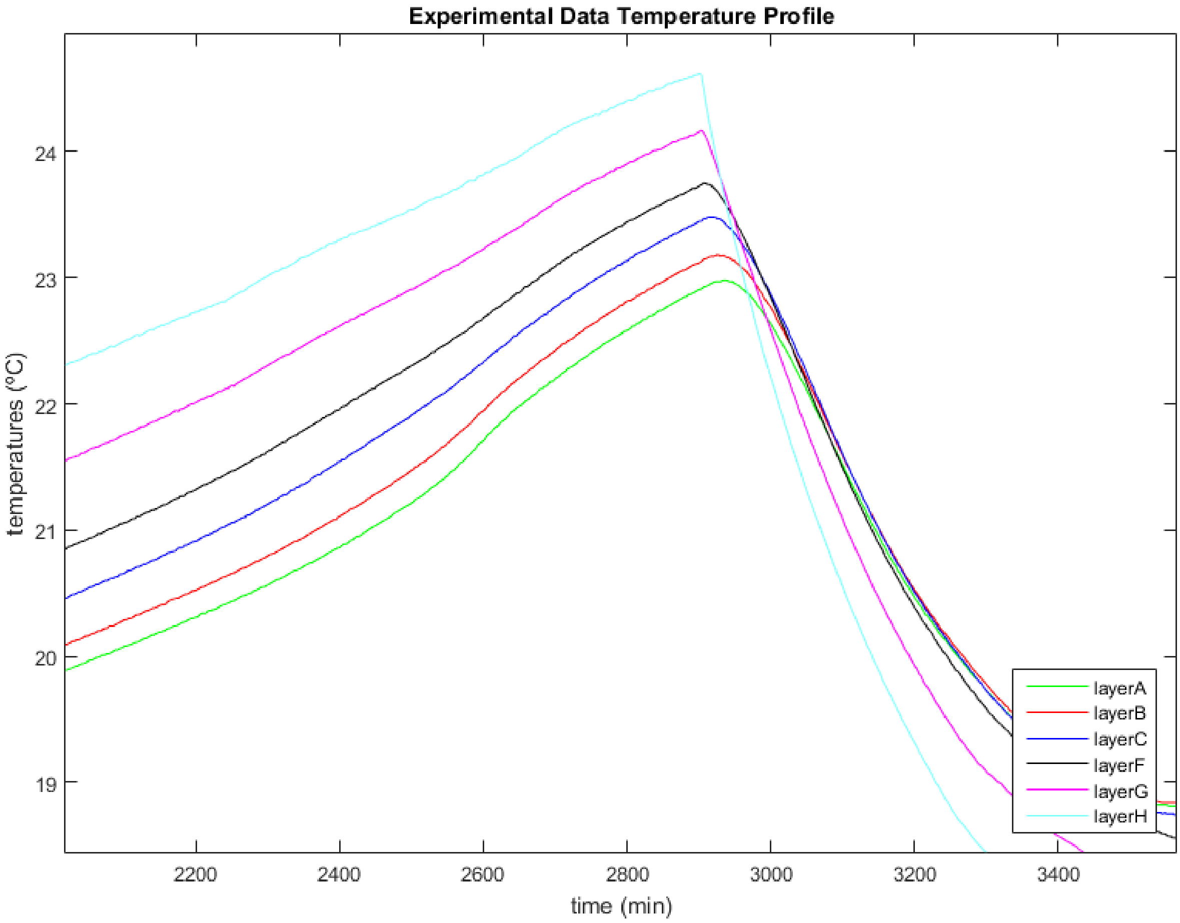

Figure 19. Close-up of phase transition

5.1.2 Cooling down: discharging of wall

The freezing curve shown in Figure 20 shows two different regions:

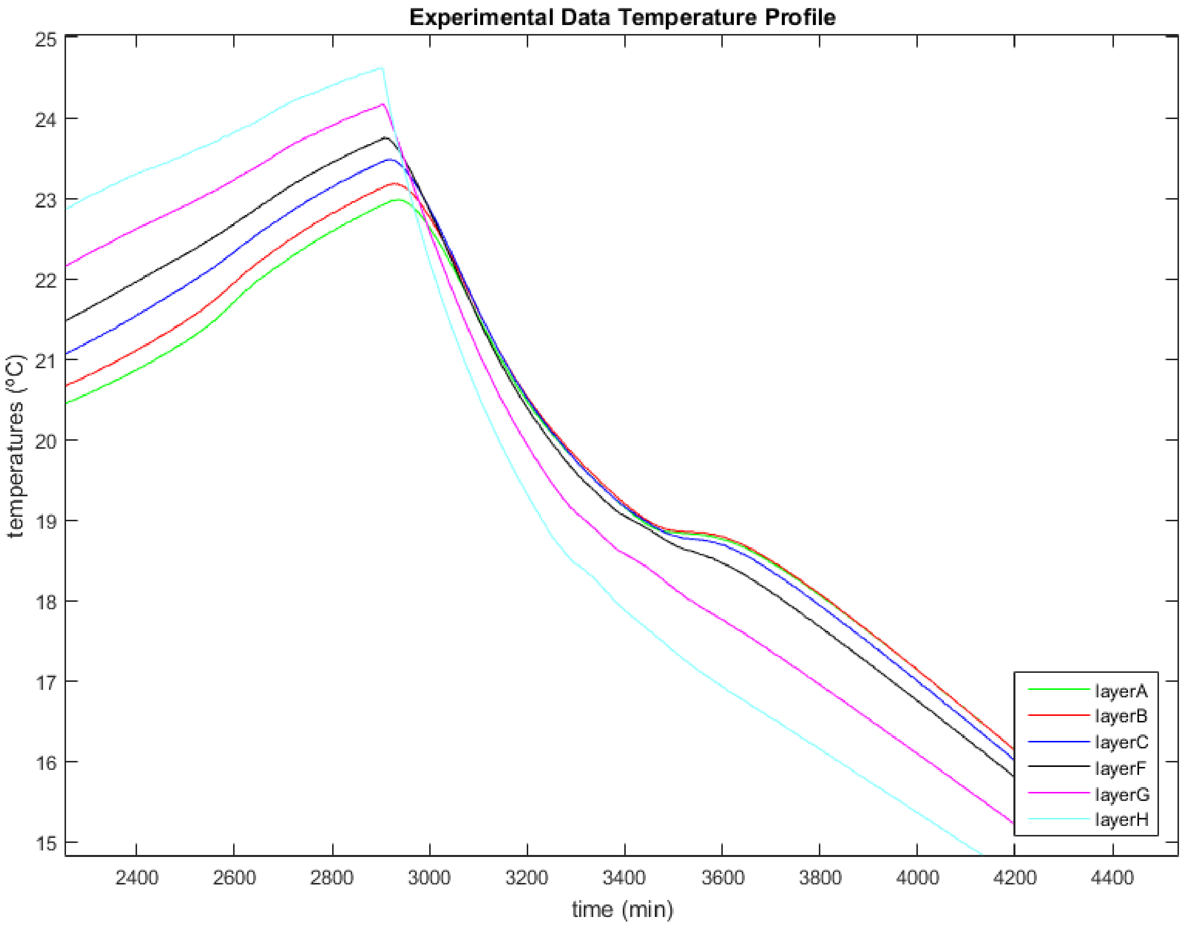

Figure 20. Cooling down: Discharging of PCM wall

From $time = 3000\,min$ to $time = 3500\,min$, where the curves drop abruptly: the temperature difference between the room (and panels) and the outside is at its largest. An interesting effect can be observed at the cooling region. The curves quickly gather together, which means that the layers are all at the same temperature almost at the same time. There are two main reasons for this: Firstly, when the heater is turned off, the first layers are more sensitive to this change so they rapidly start to cool down. The last layers however are still being warmed up by their preceding ones, so they do not start cooling down as fast as the first layers, and when they do, because they are always colder than the first ones, they cool down at a slower pace.

After the panels drop to about 19-18ºC, around the freezing range, the panels begin to cool down more slowly. Again, the phase transition is easier to observe on the outer panels.

The phase change is much more evident in the freezing phase, probably because the cooling rate at the freezing point is faster than the warming rate at the melting point.

By looking at Figure 18 and Figure 19 the melting point for our experiment is located at around 21-22ºC, which is around 1ºC less than the point measured by Kuznik (22.3ºC), and covers the value given by the manufacturer (21.7ºC). The freezing point (Figure 20) is around 18-19ºC, this time a bit higher than the value measured by Kuznik (17.8ºC), so here the difference is smaller.

It is necessary to reflect on the significance of these melting and freezing points. If the panels start absorbing heat at the time they reach their melting point, 21-22ºC is quite a low melting point. A higher temperature like 25-26ºC would be more useful, as human comfort lies between 22-26ºC according to Figure 2 from Chapter 2. Nevertheless, there is always a time lag between the time the room reaches a certain temperature and the time the first panel reach the same temperature. For the freezing phase, the freezing point could be a bit higher too, around 21-22ºC. However, as it was previously metioned, our heating and freezing rates are low and these melting and freezing points may be higher for higher rates.

5.2 Analysis of the model: Variable sensitivity

The purpose of this section is to observe how much or how little each of the four variables that we determined in the previous chapter affects the charging and discharging of the PCM. We will comment and evaluate if they are consistent with the experimental data, modifying them when necessary.

To analyze each variable, we compare the model to the experimental data. To make things easier, the model is compared to the experimental data *but the first and last layers of the model are matched to the first and last layers of the actual experimental data.* By doing so we can see how the layers in between react to the change of each variable. Of course now that the model is constrained, it does not work exactly as it should, but this is only done in order to improve the accuracy of our properties and with it the model itself.

The three 'constant' variables are analyzed: PCM thermal conductivity, PCM density and air convection coefficient. For these three, we will try different, reasonable values for each of them, fixing the other two. The three properties are analyzed at both the warming and freezing process. After studying them, the much more complex heat capacity is analyzed.

All of the following graphs give the temperature of each layer against time. The dashed lines correspond to the experimental data and the continuous line to the model. Bear in mind that in this section the model has the temperature from the first and last layers (H and A) matched to the experimental data temperatures.

5.2.1 Thermal Conductivity

As it was mentioned in the last chapter, the conductivity value has been taken from the panel's manufacturer (DuPont Energain): $k(solid) = 0.18\, W/mK$ and $k(liquid) = 0.14\, W/mK$ [5]. As we have seen, it is hard to tell the exact point where the material changes phase and so it is difficult to implement both values.

Different conductivity values (Figures 21 to 24) have been tested in our model to see how big their effect is and which value best suits:

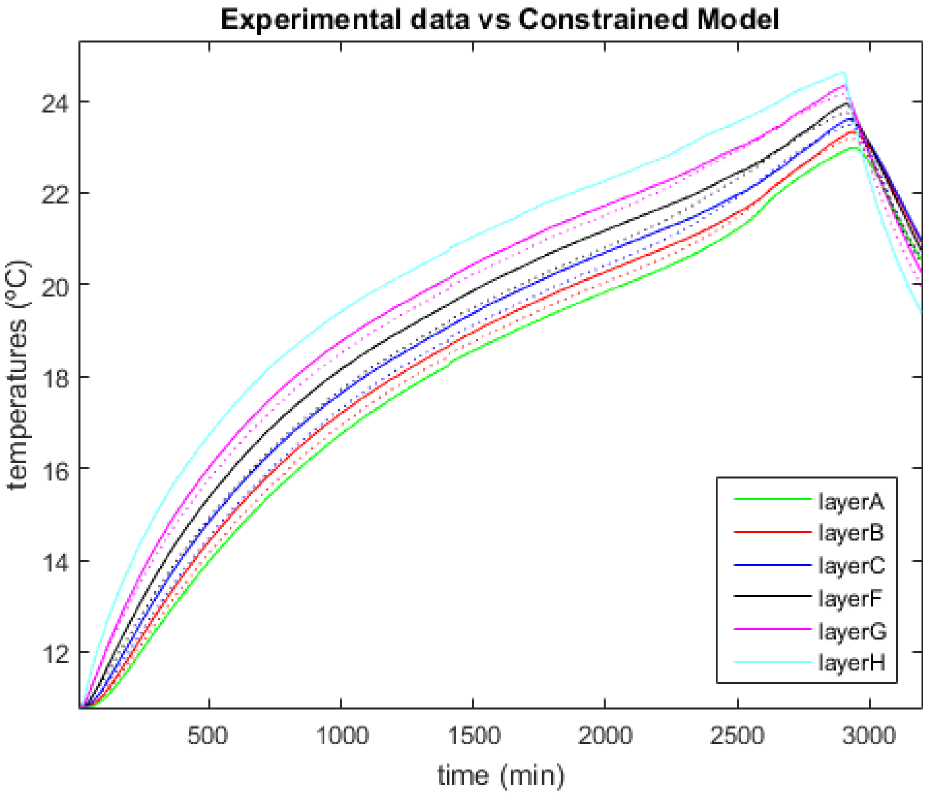

Figure 21. PCM Temperature vs Time. k=0.05 W/mK.
Dashed line: experiments. Continuous line: model

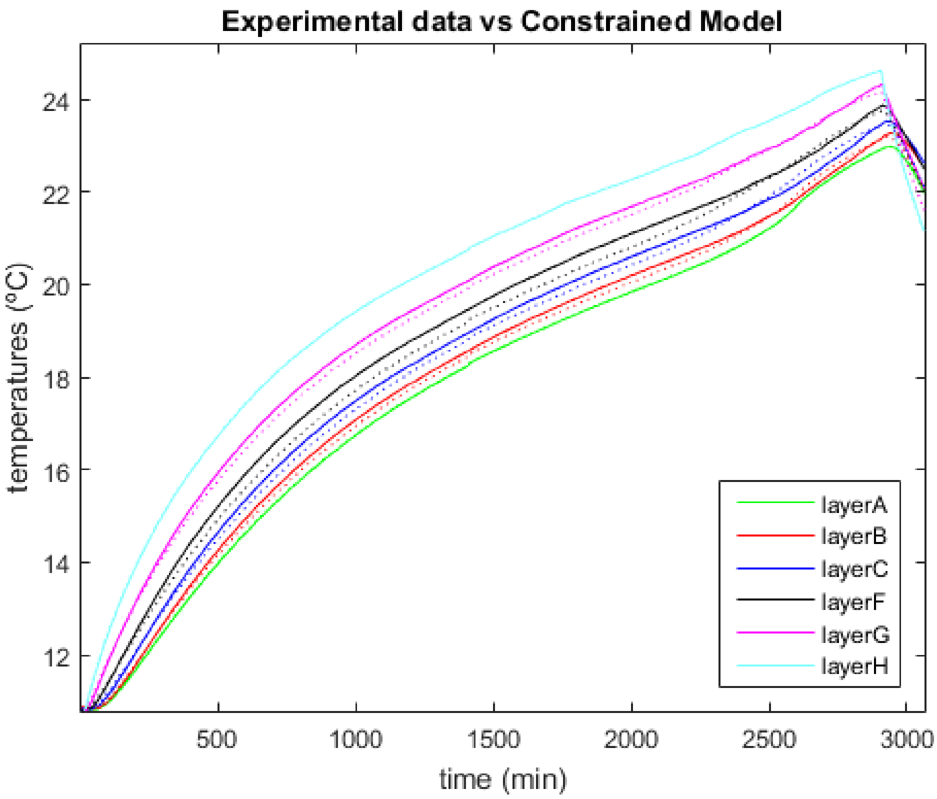

Figure 22. PCM Temperature vs Time. k=0.10 W/mK.
Dashed line: experiments. Continuous line: model

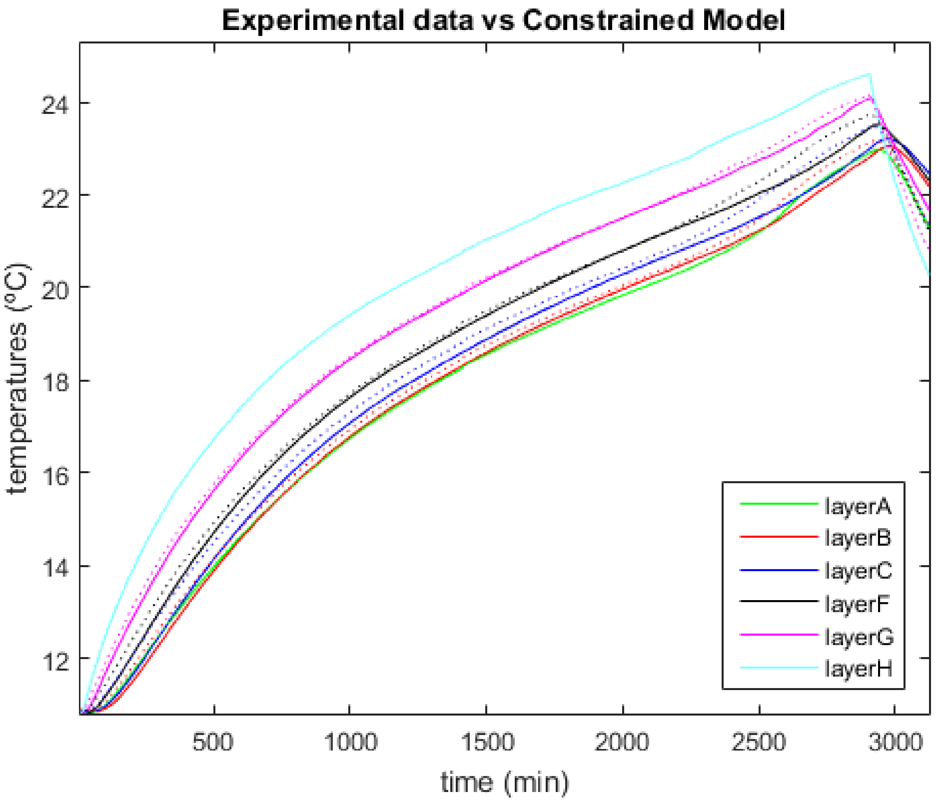

Figure 23. PCM Temperature vs Time. k=0.15 W/mK.
Dashed line: experiments. Continuous line: model

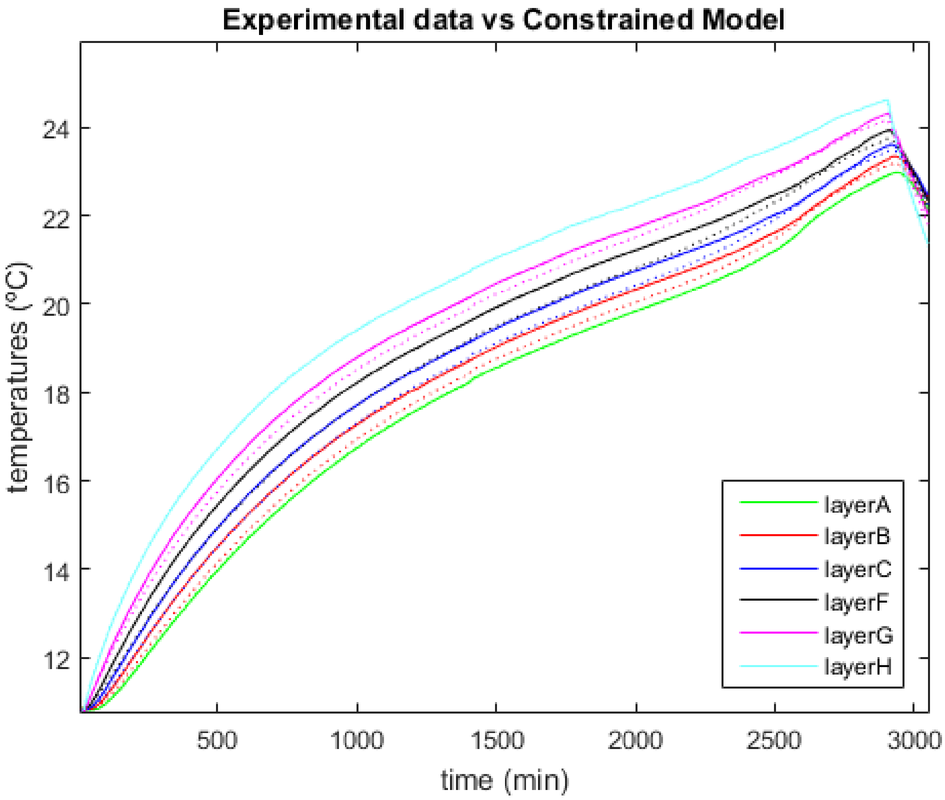

Figure 24. PCM Temperature vs Time. k=0.20 W/mK. Dashed line: experiments. Continuous line: model

We can see that, at the beginning, for the last two graphs (Figure 23 & Figure 24), $k = 0.15\,W/mK$ and $k = 0.20\,W/mK$, the curves from our model are steeper, which means that in the model the panels would be warming up faster that what the actual data suggests. A value of $k = 0.15\,W/mK$ looks good, but it does not work very well after the phase change, which is necessary. The first two graphs (Figure 21 & Figure 22), with lower conductivity than expected, $k = 0.05\,W/mK$ and $k = 0.10\,W/mK$, warm up at similar rates than the panels.

At around 21 ºC, close to the melting point, the panels start to warm up a bit quicker which can correspond to a higher conductivity. Even though the manufacturer stated a lower conductivity for the liquid phase, Kuznik [3] also measured the PCM conductivity for both phases, and he obtained a higher value for the liquid PCM ($k_{liquid} = 0.22\,W/mK$ vs $k_{solid} = 0.18\,W/mK$). This discrepancy could indicate that the error for one pair of measurements (either the manufacturer's or Kuznik's) is important; another reason to set a constant value.

It should be taken into account that these curves depict a phase change. So it is difficult to relate the aspect of these curves around the melting point/range to just one parameter.

A similar approach is done for the freezing process. As with the melting process, the conductivity is lower than expected, also around $k = 0.10\,W/mK$

Because the panels change phase in a range of temperature, it is difficult to separate clearly one phase from the other. This value is lower than the one stated by the manufacturer. It could be due to the fact that the experiment uses five layers of the material instead of a small sample which is how the conductivity is normally measured. In addition, each PCM panel is protected around the edges by aluminum tape, which can decrease the total conductivity. Also, there is contact resistance between every pair of panels. In addition, the thermocouples are surrounded by tape to avoid being affected by thermocouples close by.

In conclusion, the model is simplified by fixing the conductivity to $k = 0.10\ W/mK$. The model is also simplified by the fact that now for any time, $kw = ke$.

5.2.2 Convection

Figures 25 to 27 show the model compared to the experimental data for different values of the air convection coefficient h_{int}:

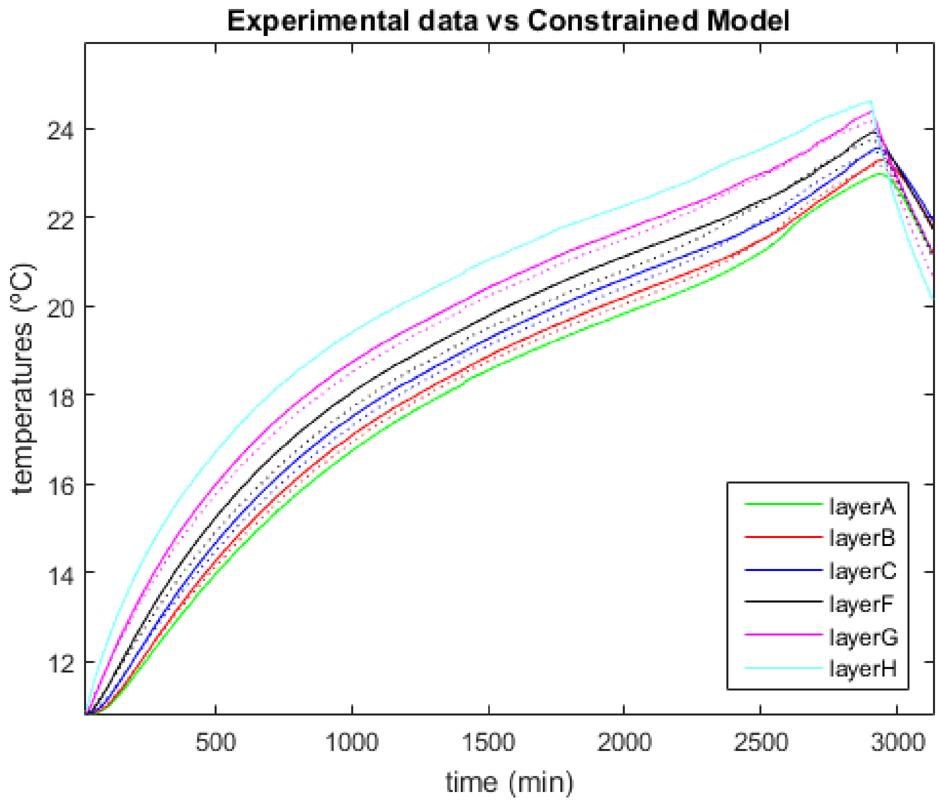

Figure 25. PCM Temperature vs Time. h_{int}= 5 W/m^2 K.
Dashed line: experiments. Continuous line: model

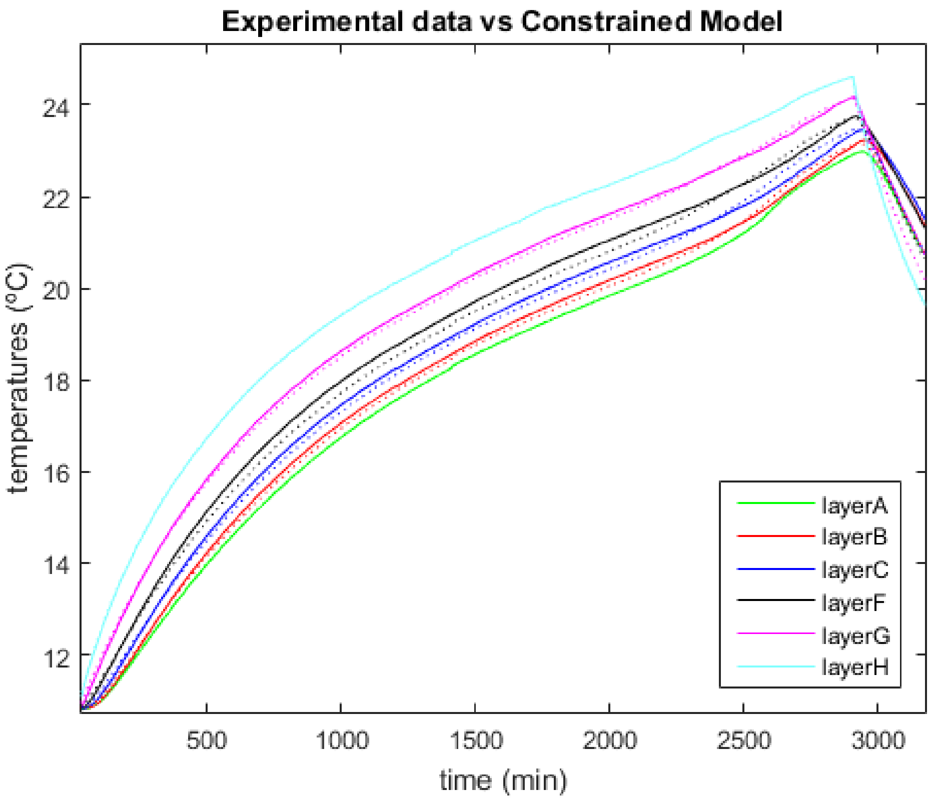

Figure 26. PCM Temperature vs Time. h_{int}= 10 W/m^2 K.
Dashed line: experiments. Continuous line: model

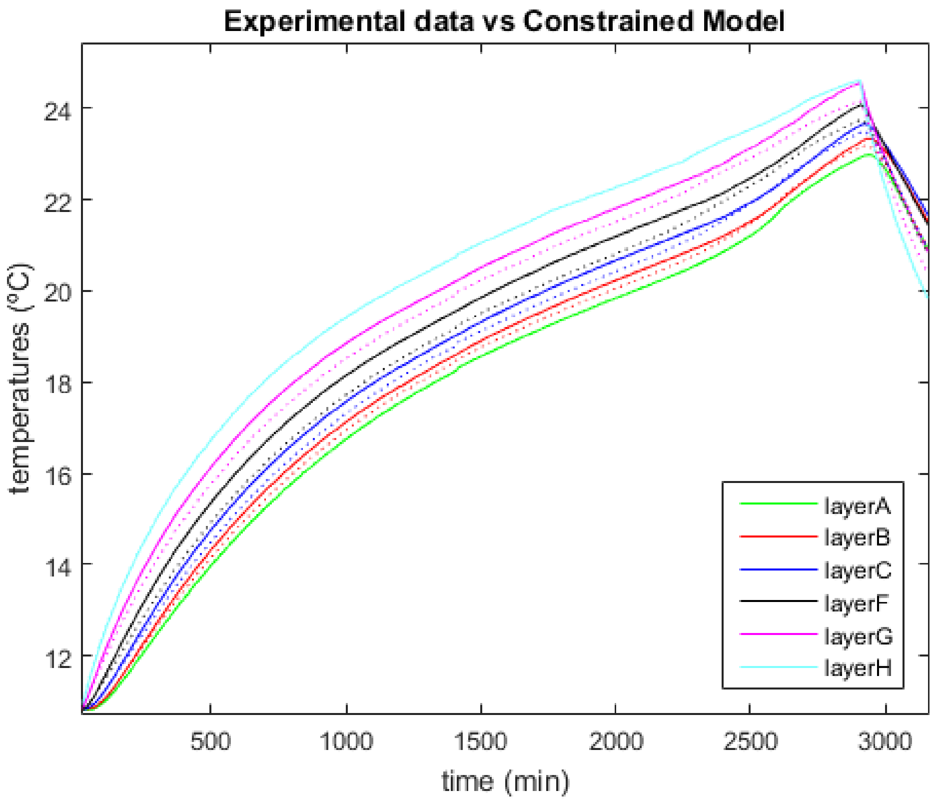

Figure 27. PCM Temperature vs Time. h_{int}= 15 W/m^2 K.
Dashed line: experiments. Continuous line: model

The graphs above prove that the convection coefficient for the interior wall could be between $h_{int} = 5\ W/m^2K$ and $h_{int} = 10\ W/m^2K$, which matches the estimated value earlier of $h_{int} = 8.6\ W/m^2K$. Thus this value is kept.

5.2.3 Density

The PCM's density can vary a little as it goes from solid to liquid or vice versa. However, the change in density is very small and can be neglected. Therefore $\rho(T) = 855.5\ kg/m^3$ (as specified by the manufacturer). The model does not show any considerable difference between using that density value and one as much as 10% higher or lower.

To finally check the validity of our model we compare it with the experimental data.

5.3 Comparison between experimental data and model

5.3.1 Graphical comparison

After setting the variables, we plot the model vs the data (See Figure 28 to 30).

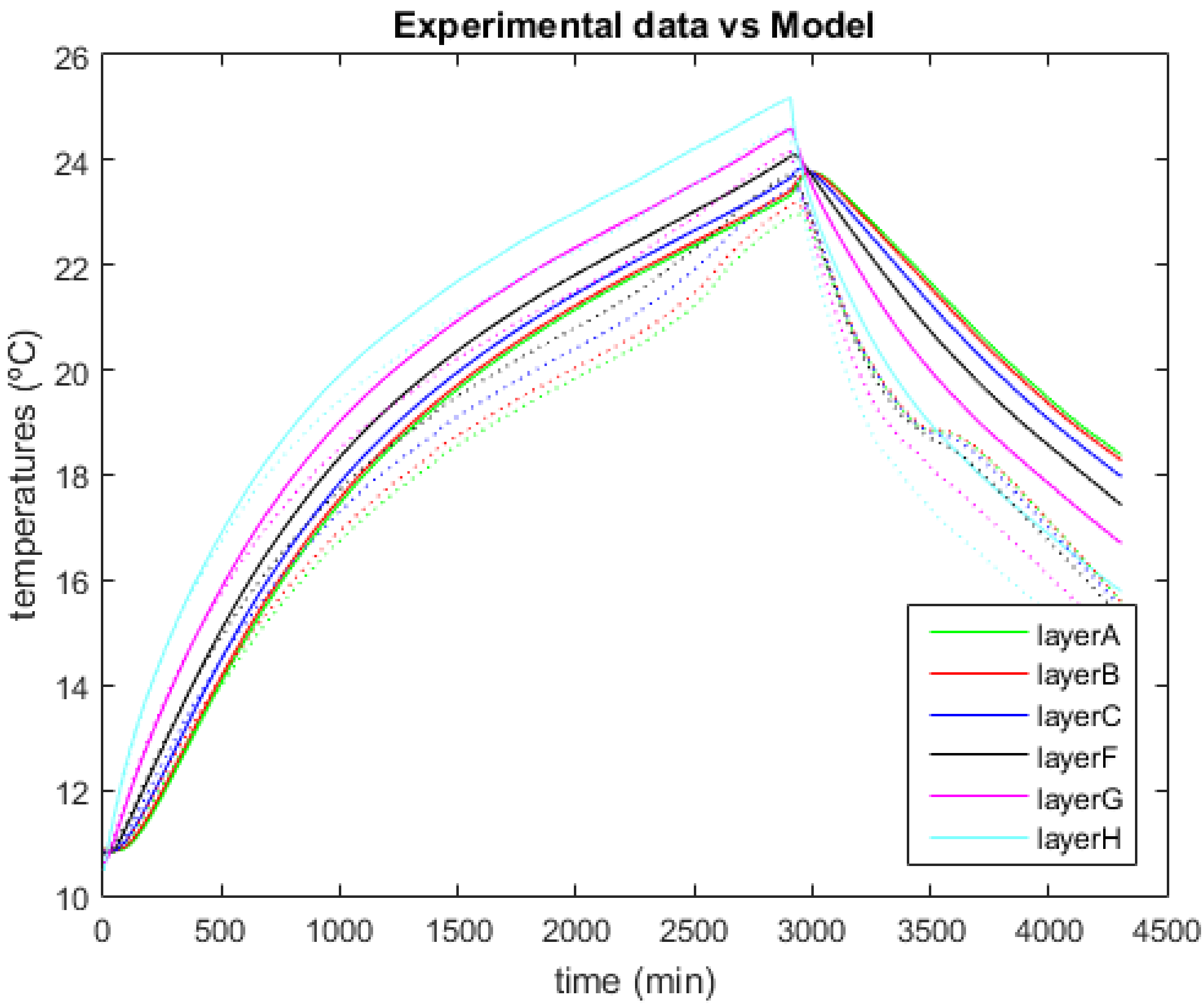

Figure 28. PCM Temperature vs Time.
Dashed line: experiments. Continuous line: model

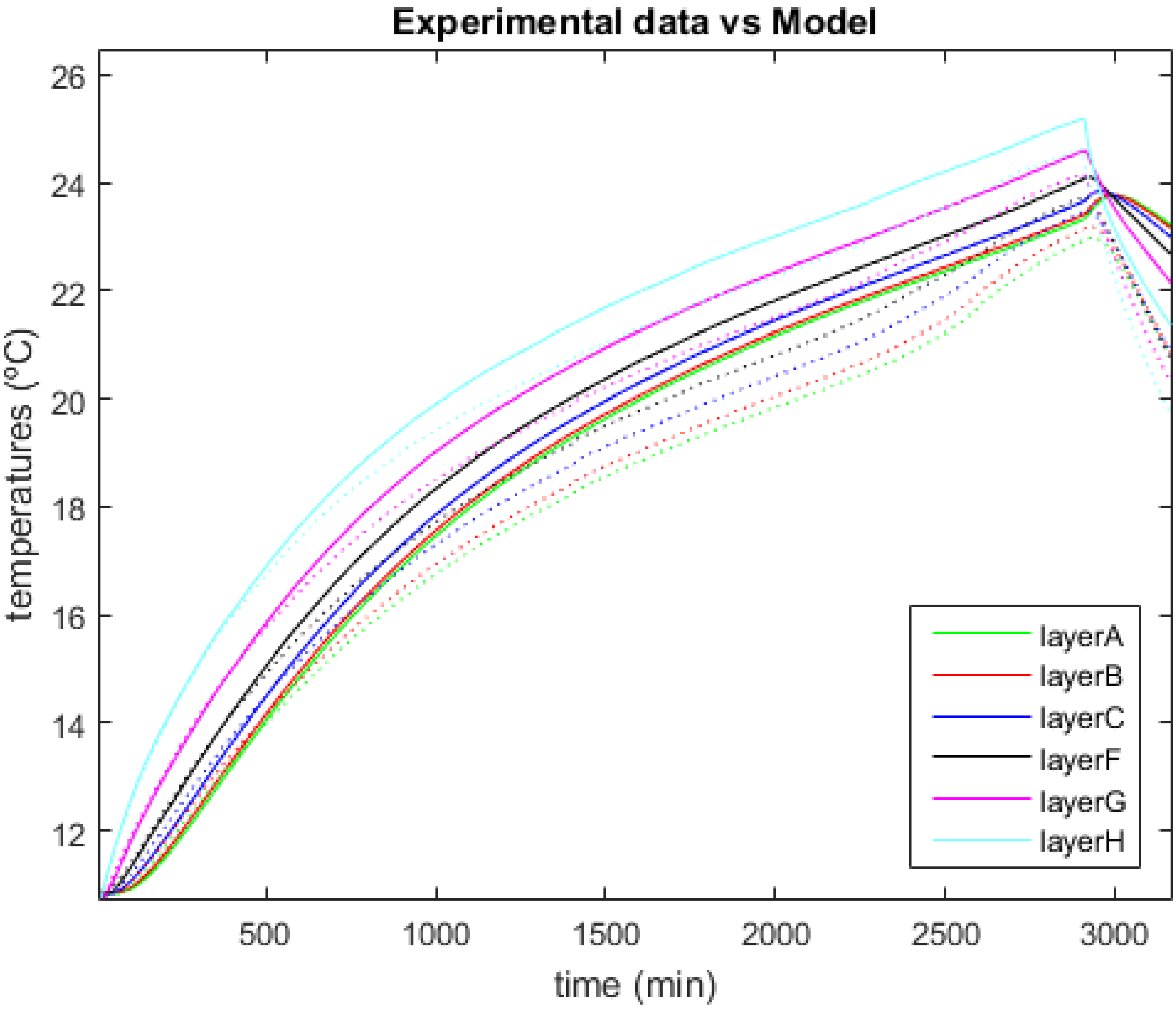

Figure 29. PCM Temperature vs Time: Melting.
Dashed line: experiments. Continuous line: model

The model is accurate at representing the distance among layers. It heats up a bit faster than the experimental data, and does not depict the phase change as sharp as what happens in reality. The biggest temperature difference between model and data is observed in the external layers and is less than 2ºC when warming up (See Figure 29 above).

In general, the freezing part is more complicated to model as the material presents hysteresis. In Figure 30 we can see the main problem that appears when the panels start cooling down: The model takes much longer to drop the panel’s temperature than in reality, especially for the external layers. Experimentally, we can see that the panels lose their heat quicker than expected by the model, which may indicate that the capacity becomes lower than predicted.

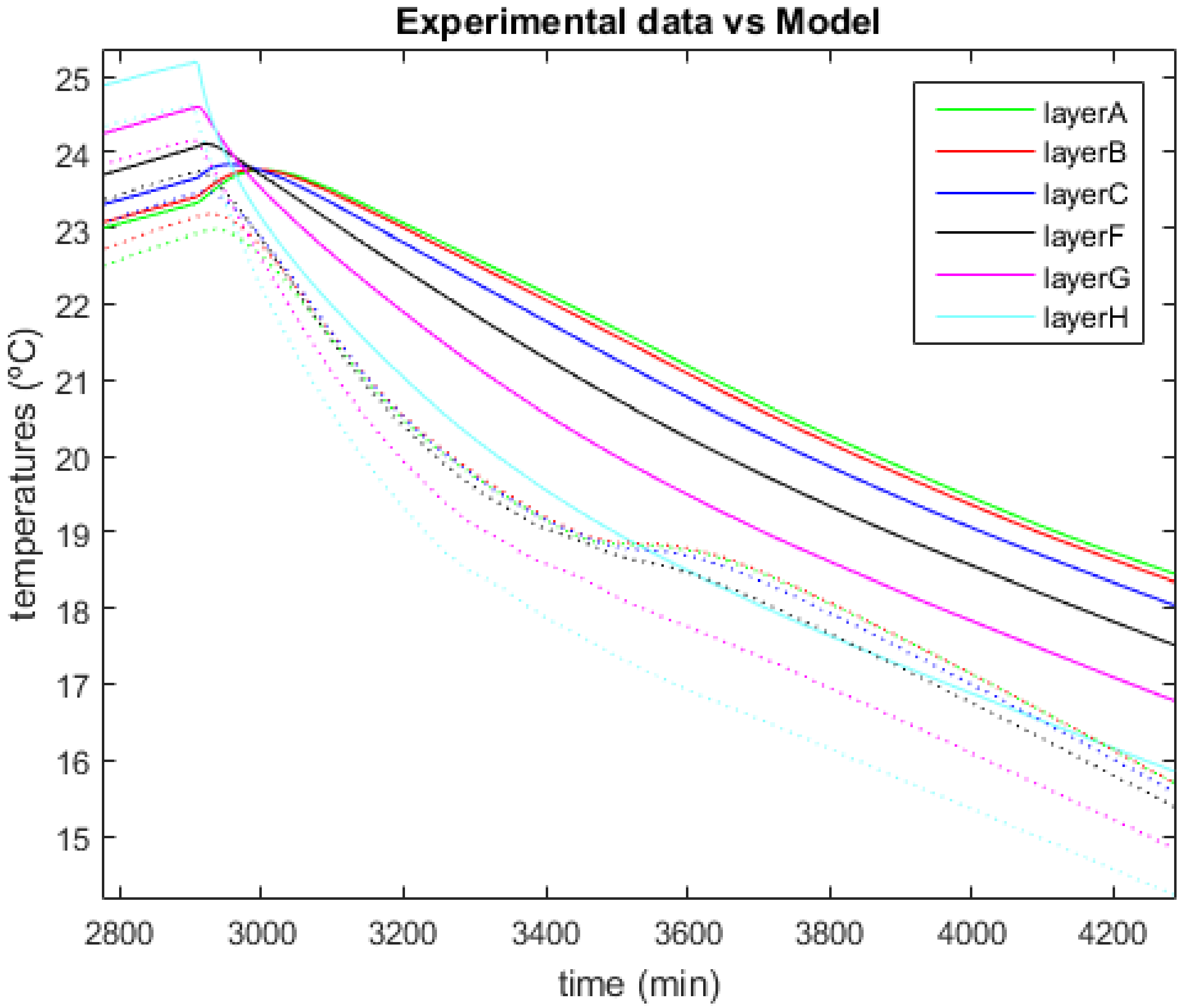

Figure 30. PCM Temperature vs Time: Freezing.
Dashed line: experiments. Continuous line: model

The biggest temperature difference between model and experimental data is also observed in the external layers. In this case is less than 3ºC (Figure 30).

It is difficult to model several PCM layers at the same time; as previously seen, external layers react a bit differently than interior layers, and the model also predicts worse the external layers. In addition, five layers do not mean five times more heat storage than with a single layer. The manufacturer recently calculated the optimal thickness for a PCM wall, concluding that 2 layers woud be best *(See Annex I)*.

Due to little information regarding the material thermal and physical properties some of these values had to be estimated and later analyzed. Out of three relevant PCM properties two (thermal conductivity, and density) are kept constant to simplify the model, as well as the air convection coefficient. Heat capacity is, logically for PCMs, highly dependent on temperature which is reflected on the model.

5.3.2 Error analysis

For a quick analysis of how well the model fits the data, we can calculate the difference between every couple of curves (experimental data and model) for each layer. The RMSD (root-mean-square deviation), also called RMSE (root-mean-square error), is a frequently used measurement of the differences between values predicted by a model and the values actually observed [25]. It is an estimator of how much the model differs from the actual data (standard deviation) by giving a single value which is easy to use. The closer to zero, the better the fit:

$$RMSD = \sqrt{\frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}{n}}$$

Equation 3. RMSD [25]

To normalize the RMSD and have a useful value, we divide it by the mean of the measurements to obtain the coefficient of variation CV(RMSD):

$$CV(RMSD) = \frac{RMSD}{\hat{y}}$$

Equation 4. Normalized RMSD [25]

This value is commonly referred to as the normalized root-mean-square deviation or error. The advantage of the CV is that it is unit less, so we can compare the deviation between the model and the experimental data among different layers. Normally, the value is expressed as the given ratio multiplied by 100 to give a percentage. The lower the CV, the smaller the residuals relative to the predicted value.

The CV(RMSD) is therefore calculated for each layer (Table 4):

Layer	CV(RMSD) (%)
A	8.59
B	8.00
C	7.18
F	6.38
G	5.80
H	5.08

Table 4. CV(RMSD) for every layer

We can see that the model predicts better the behavior of the interior layers (H, G, F), which is something to be expected; the last layer depends not only on its own properties but on its preceding layers' properties.

Chapter 6

Conclusions and further work

6.1 Conclusions

A PCM wall has firstly been experimentally studied and then modeled using MATLAB.

In the experimental part it is observed that the material behaves differently depending on whether it is warming up or cooling down. Its heat capacity depends not only on its current temperature but on its previous ones, as it holds a different capacity whether it is warming up or cooling down.

The PCM does not have a precise phase change temperature but rather a phase change temperature interval. Strictly speaking, it has *two* phase change temperature intervals, one for the solid-to-liquid transition and the other in the opposite direction. This poses an added challenge when modelling a PCM. The freezing point is slightly lower than the melting one.

The model has been compared to the data obtained in the laboratory and both a visual comparison and an error analysis suggest a reasonably good model fit, with maximum temperature differences between predicted and actual values by less than 3ºC or less than 9% root-mean-square error. The model is better at predicting the warming phase. The heat capacity curves, taken from a slightly different experiment may be the main reason that the model does not provide a perfect fit.

Five layers may have been too many to study; on one hand the model fit is reduced as the number of layers increases and on the other hand more layers does not necessarily mean more information. (After the experiment had taken place, the manufacturer calculated the optimal number of panels pertinent to heat storage. (See *Section 9.1 Annex I*)

6.2 Further work

More experimental data has to be compared with the model to better assess its fit.

Actual heat capacity temperature dependence can be studied or even measured to fully understand the panels' behaviour. Conductivity and convection temperature dependence with temperature may be studied as well.

It would be interesting to perform the same experiment by starting with only one layer of PCM and then proceed to add one extra layer at a time to understand how much each extra panel accounts for.

The energy stored and released by the panels during the experiment can be calculated and analyzed, in order to find the optimal thickness/area of PCM needed for any site.

The panels are not actually receiving energy from the Sun but rather from a constant energy indoor input source. The same experiment may be carried out on real life conditions to account for the effects of e.g. solar radiation spectrum, relative movement of the Sun to the wall, window transmissivity, etc. The experiment also takes too long to be considered as a real case. The time can be reduced to match a day's hours of sun time and the heating/cooling rate increased to study the actual temperature profile during the day and night.

Some other ideas to continue working may include:

- Perform exactly the same trial with and without PCM.
- Add PCMs on other walls/ceiling from the same test room.
- Prove that the back wall between PCMs and exterior is reasonably insulated or more/less insulation is needed.
- Study the gradient of temperatures within a panel by placing thermocouples in the center and edges/corners of the panel.
- Study the dependence of phase changing temperatures with heating/cooling rates to choose the perfect PCM for every rate.

Chapter 7

Budget

Below is an estimation of the costs of this project. This is only a simple approximation and some costs may be higher/lower than estimated. Costs can be divided into direct and indirect costs. The time considered for the realization of this project is 260.4 hours, corresponding to a work of 4 hours per working day for 3 months. For all the costs known in Canadian dollars, the exchange rate applied is 1 CAD = 0.71 EUR (01/jun/2014) [26].

7.1 Direct costs

7.1.1 Workforce

The work was divided between my mentor, a Masters Engineering student, and me, an undergraduate engineering student. Hourly rates were taken from Concordia University Research Teacher and Research Assistants Collective Agreement [27] (See Table 5):

Category	Hourly Rate (€)	Working hours	Total Cost (€)
Undergraduate Eng. Student	10	260	2607
Masters Eng. Student	13	260	3349
Total	/	**521**	**5955**

Table 5. Workforce costs

7.1.2 Equipment

Equipment in general is calculated considering a utilization time of 100 hours: The actual duration of the experiment (~70 hours) plus preparation time (~30 hours). The rest of the time the same room and PCM are being used in other experiments. Cost of facilities, the environmental chamber, has been estimated as one third of the entire laboratory (Solar Simulator & Environmental Chamber) cost ($4.6 M) [4].

The room and the materials used in the experiment are roughly estimated as 10 000€. The materials include: high-accuracy PID controllers and thermocouples, one heater, one air fan, and others.

PCM cost is estimated as 10€/kg [28]. Given that each panel weighs 5.4 kg and 20 panels are used, a total cost of 1080 € is obtained.

The laptop used to write the project and run the software used (MATLAB) costs 699 €, and has a depreciation time of about 3 years. A Spanish MATLAB student license costs 377 € and it is only valid for my student years (5 years).

The cost chargeable to the experiment itself is calculated using the following formula:

$$\text{Chargeable cost (€)} = \text{Total cost (€)} * \frac{\text{Time used (hours)}}{\text{Depretiation time (hours)}}$$

Equation 5. Chargeable cost of equipment

It is considered a depreciation time for both the laboratory facilities and materials of 43776 hours (5 years) except for the laptop (3 years).

Below in Table 6 one can see the total equipment chargeable cost of the experiment:

Equipment	Cost (€)	Use (hours)	% use in total project time	Depreciation period (months)	Chargeable cost
Lab facilities	1065000	100	38	60	2433
PCM room & materials	10000	100	38	60	23
PCM	1080	100	38	60	2
Laptop	699	260	100	36	7
Software	377	60	23	60	1
Total	**1075000**	/	/	/	**2466**

Table 6. Equipment costs

The facilities are extremely expensive so the total cost of the facilities accounts for about 99% of the total equipment cost. Thankfully, the experiment was very short lived compared to the total depreciation time of the facility so the total chargeable cost of the experiment is low.

7.2 Indirect costs

Indirect cost may include maintenance of facilities and machinery, administration and human resources, electricity and other utilities, among others. It is very difficult to calculate so it is estimated as 10% of total cost:

$$Indirect\ costs\ (€) = 0.01 * \ Direct\ costs\ (€) = 842$$

Equation 6. Indirect costs

7.3 Total costs

Table 7 breaks down the total cost into direct (workforce + equipment) and indirect costs:

Concept	Total Cost
Workforce	5955
Equipment	2466
Indirect Costs	842
Total	**9263**

Table 7. Total costs

The total budget for this project amounts to 9263€

Chapter 8

References

[1] Dermardiros, Vasken, Bastien, Diane. *Model predictive control of building-integrated thermal storage based on phase change materials*. Optimized Operation and Energy Efficiency: Towards High Performance Buildings. Montreal, Canada, s.n., 2014.

[2] Consejo Superior de Investigaciones Científicas (CSIC). *Materiales de construcción* [Online] http://materconstrucc.revistas.csic.es/index.php/materconstrucc [Accessed 10th July 2015].

[3] F. Kuznik, J. Virgone, *Experimental investigation of wallboard containing phase change material,* Energy and Buildings 41(2009) 561-570.

[4] *Centre for Zero Energy Building Studies, Concordia University* [Online] http://www.concordia.ca/research/zero-energy-building/facilities/labs-equipment.html [Accessed 10th July 2015].

[5] Du Pont™ Energain ® [Online] http://energain.co.uk/Energain/en_GB/index.html [Accessed 10th July 2015].

[6] SavEngr, *Phase Change Energy Storage Technology* [Online] http://www.rgees.com/technology.php [Accessed 10th July 2015].

[7] Feuste, H.E., C. Stetiu. *Thermal Performance of Phase Change Wallboard for Residential Cooling Application.* Lawrence Berkeley National Laboratory.

[8] F. Kuznik, J. Virgone, *Experimental assessment of a phase change material for wall building use.* Applied Energy 86 (2009) 2038–2046.

[9] Australian Government, *Australia's guide to environmentally sustainable homes* [Online] http://www.yourhome.gov.au/materials/lightweight-framing. [Accessed 10th July 2015].

[10] Ramprasad Chandrasekharan Edwin S. Lee Daniel E. Fisher, PhD. *An Enhanced Simulation Model for Building Envelopes with Phase Change Materials.* [Online] http://www.phasechange.com/Research%20Library/An_Enhanced_Simulation_Model_for_Building_Envelopes_with_Phase_Change_Materials.pdf [Accessed 10th July 2015].

[11] Prof. Dr. Klaus Sedlbauer, Dipl.-Ing. Hans Erhorn, Dr.-Ing. Andreas Holm, Dipl.-Ing. *Energy efficiency and room climate - Symbiosis or contradiction.* Tür-Tor-Fenster-Report 26 (2006), Nr.5, S.18-23 ISSN: 0724-7702.

[12] A. Oliver, F. J. Neila, A. García-Santos. *PCM choosing and classification according to their characteristics for their application for thermal energy storage systems.* Mater. Construcc., 2012, Vol. 62. ISSN: 0465-2746.

[13] Ltd, PCM Products, *Phase Change Materials: Thermal Energy Storage* [Online] http://www.pcmproducts.net/Solid_Solid_PCMs.htm [Accessed 10th July 2015].

[14] Climate Tech Wiki, *Energy Storage: Phase Change Materials for Thermal Energy Storage*. [Online] http://www.climatetechwiki.org/technology/jiqweb-pcm-0# [Accessed 10th July 2015].

[15] Karim Lee, Ali. 2014. *Application of PCM to shift and shave peak demand: Parametric studies.* Masters thesis, Concordia University (2014).

[16] PureTemp, *Global Authority on Phase Change Material* [Online] http://www.puretemp.com/ [Accessed 10th July 2015].

[17] US National Renewable Energy Laboratory*, Leading Clean Energy Innovation* . [Online] http://www.nrel.gov/csp/troughnet/thermal_energy_storage.html#media [Accessed 10th July 2015].

[18] Omer, A, *Renewable building energy systems and passive human comfort solutions.* Renewable and Sustainable Energy Reviews, Volume 12, Issue 6, August 2008, Pages 1562–1587.

[19] Du Pont, *Our Company* [Online] http://www.dupont.com/ [Accessed 10th July 2015].

[20] *PCM panel picture* [Online]
http://www.e-architect.co.uk/images/jpgs/products/dupont_energain_panel_q051011.jpg
[Accessed 10th July 2015].

[21] Energy Plus, *Engineering Reference: Surface Heat Balance Manager Processes* [Online] http://nrel.github.io/EnergyPlus/EngineeringReference/03-SurfaceHeatBalance/#conduction-finite-difference-solution-algorithm [Accessed 10th July 2015].

[22] Solomona, Gnanadurai Ravikumar, *Sub cooling of PCM due to various effects during solidification in a vertical concentric tube thermal storage unit,* Applied Thermal Engineering, Volume 52, Issue 2, 15 April 2013, Pages 505–511.

[23] E. Günther, S. Hiebler, H. Mehling. *Determination of the heat storage capacity of PCM and PCM-objects as a funcion of temperature,* Ecostock 2006 Conference.

[24] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. *Ashrae Handbook Fundamentals* 2009 Section 4.19 ISBN 978-1-933742-54-0.

[25] UCLA Institute for Higher Research and Education, *Coefficient of variation* [Online] http://www.ats.ucla.edu/stat/mult_pkg/faq/general/coefficient_of_variation.htm. [Accessed 10th July 2015].

[26] XE, *Current and Historical Rate Tables* [Online] http://www.xe.com/currencytables/ [Accessed 10th July 2015].

[27] *Teaching and Research Assistants at Concordia (TRAC)* [Online] http://trac-union.ca [Accessed 10th July 2015].

[28] Jan Kosny, Nitin Shukla, and Ali Fallahi, *Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Climate,* Building Technologies Program, January 2013 [Online] http://www.nrel.gov/docs/fy13osti/55553.pdf

Chapter 9

Annex

9.1 Annex I: Energy storage

After the experiment had been carried out, the manufacturer calculated and published the relationship between the amount of heat stored and released by the panels and the thickness of a wall made of its PCM [5].

Comparing to concrete, a typical construction material, the PCM optimal thickness is much lower: 10 mm (2 PCM panels) (Figure 32) against 80mm for concrete (Figure 31). Both materials store similar amounts of energy at their optimal thickness (about 130 Wh/m2).

There is not much additional gain in energy storage between a panel (5mm) and 2 panels (10 mm). At the thickness of a single panel the heat storage performance is around 75% of the total. In comparison, concrete reaches 75% of its total performance at 25mm, at less than half its optimal thickness (80mm).

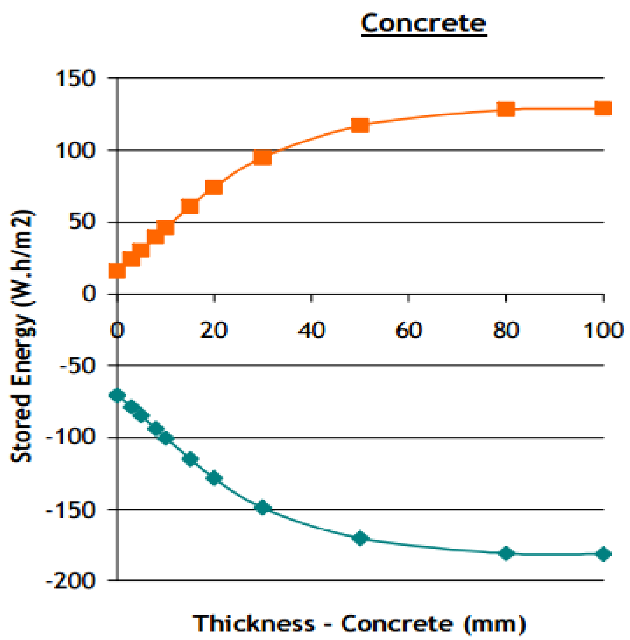

Figure 31. Concrete Stored energy vs thickness [5]

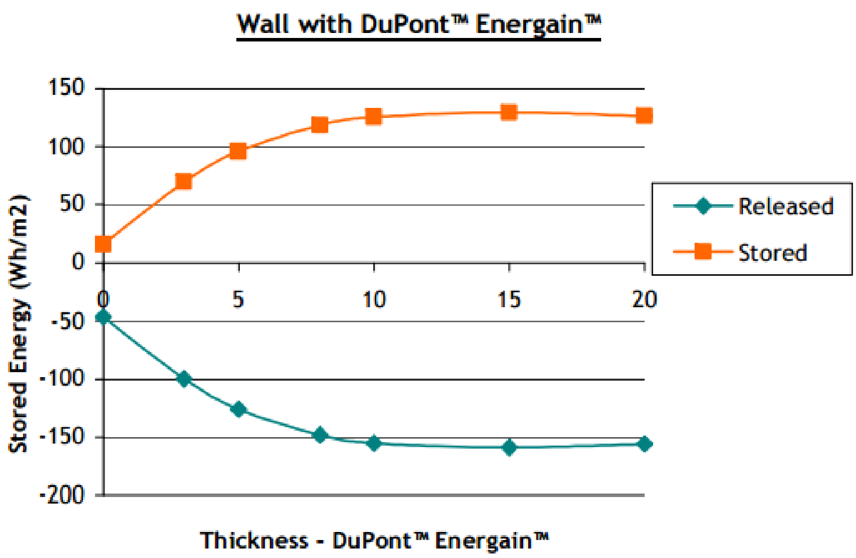

Figure 32. PCM Stored energy vs thickness [5]

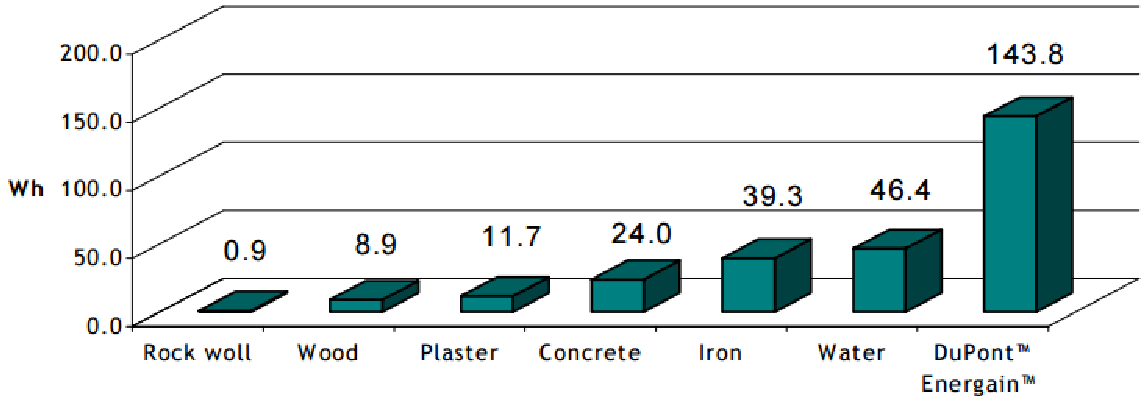

Figure 33. Total heat exchanged for 5mm thickness with the temperature between 18 ºC and 24 ºC [5]

Now, for the optimal PCM thickness, Figure 33 compares the total heat exchanged for different construction materials, including concrete and PCM. Figure 33 shows a ratio of 5 (143.8Wh/24.0Wh) between the energy stored by the PCM panel and the concrete for a temperature change between 18 ºC and 24 ºC. It is important to take into account that the optimal PCM thickness is used for the comparison, and 5mm concrete is not strictly equivalent to a 5mm PCM, and only the latent heat interval of the PCM is being considered. Thus, this ratio of 5 is theoretical and the actual ratio between these two materials is usually lower.

9.2 Annex II: MATLAB code

9.2.1 MATLAB model code

This is the MATLAB code I used to model the wall

```
% Vector initializes with first data from initial values from experiment
Tj=[Var2bA4(1),Var2bB4(1),Var2bC4(1),Var2bF4(1),Var2bG4(1),Var2bH4(1)]';
Tint=Var2bI4(1);

% Cp equation (by default uses Cp melting)
 cp=interp1(TempMelting,CpMelting,Tj,'pchip')*1000;

 % Tsim is vector 1 by 1436, 1436 time steps is the duration of the melting
phase (1436 3-min time steps is around 500 min)
Tsim=zeros(1,1436);

 % dx is finite difference thickness, half thickness for layer H and A
dx2=zeros(6,1);
for i=2:5
    dx2(i)=5.2e-3;
end
dx2(1)=(5.2e-3)/2;
dx2(6)=(5.2e-3)/2;

% convection coefficient
h=8.6;
```

```
%term for first equations convective heat transfer
d=zeros(6,1);
d(6)=h*Tint;

%cp curve varies whether the panel is warming up or cooling down. To see
%which ones the case, I compare each panel with its previous temperature.
%Tjstore1=Temperature at t
%Tjstore2=Temperature at t+1
Tjstore1=zeros(6,1);
Tjstore2=zeros(6,1);
for i=1:6
Tjstore1(i)=Tj(i);
end

Temp=zeros(6,1436);
time=zeros(1,1436);

for n=1:1436
% density
p=855.5;

a=p*dx2.*cp/dt;

Ke=0.1;
Kw=0.1;
    b=Ke/dx;
    c=Kw/dx;

    %d
    d=zeros(6,1);
    d(6)=h*Tint;

    %Lets fill matrix M
     M=zeros(6,6);
     M(1,1)=a(1)+c;
       for i=2:6
        M(i,i)=a(i)+b+c;
        M(i,i-1)=-b;
        M(i-1,i)=-c;
       end
     M(6,6)=a(6)+b+h;
     clear i

       for i=1:6
        Temp(i,n)=Tj(i);
        time(n)=n*3;
       end

       TA(n)=Temp(1,n);
       TB(n)=Temp(2,n);
       TC(n)=Temp(3,n);
       TF(n)=Temp(4,n);
       TG(n)=Temp(5,n);
       TH(n)=Temp(6,n);

        Tj=M\(a.*Tj+d);

    % In case I want to fix A and H layers:
    %     Tj(1)=Var2bA4(n);
    %     Tj(6)=Var2bH4(n);


        Tint=Var2bI4(n);
        Tjstore2=Tj;
```

```
         if Tjstore2>Tjstore1
             cp=interp1(TempMelting,CpMelting,Tj,'pchip')*1000;
        else
             cp=interp1(TempFreezing,CpFreezing,Tj,'pchip')*1000;
        end

        Tjstore1=Tjstore2;
      End

    Tj;
    Tint;
    cp;

    %code for showing also the experimental data

    % heat source Q=350W
    %to plot against time
    %var is a vector with the temperatures of the layers (layerA=1, layer
    %H=6)
    Var=[Var2bA4(1),Var2bB4(1),Var2bC4(1),Var2bF4(1),Var2bG4(1),Var2bH4(1)];
    Tint=Var2bI4(1);
    Tem=zeros(6,1436);
    time=zeros(1,1436);
    for i=1:1436;
    Var(1)=Var2bA4(i);
    Var(2)=Var2bB4(i);
    Var(3)=Var2bC4(i);
    Var(4)=Var2bF4(i);
    Var(5)=Var2bG4(i);
    Var(6)=Var2bH4(i);
Tint=Var2bI4(i);

  for p=1:6
   Tem(p,i)=Var(p);
   time(i)=i*3;

  end

end
set(0,'DefaultAxesColorOrder',[0 1 0;1 0 0;0 0 1;0 0 0;1 0 1;0.5 1 1])
hola=figure;


    plot(time,Temp,'-',time,Tem,':');

    xlabel('time (min)')
    ylabel('temperatures (°C)')
    hold all

legend('layerA','layerB','layerC','layerF','layerG','layerH','location','northea
st')
title('Experimental data vs Model')
```

9.2.2 Melting and freezing heat capacity curves data

Melting curve

Temperature(ºC)	Cp (J/gK)
1.000E+000	3.305E+000
4.921E+000	3.636E+000
1.026E+001	4.449E+000
1.385E+001	5.441E+000
1.662E+001	6.814E+000
1.874E+001	8.492E+000
2.015E+001	1.012E+001
2.170E+001	1.215E+001
2.260E+001	1.330E+001
2.292E+001	1.350E+001
2.324E+001	1.325E+001
2.356E+001	1.236E+001
2.382E+001	1.075E+001
2.407E+001	8.466E+000

Freezing curve

Temperature(ºC)	Cp (J/gK)
1.257E+000	3.559E+000
3.571E+000	3.737E+000
6.784E+000	4.220E+000
9.034E+000	4.729E+000
1.193E+001	5.720E+000
1.385E+001	6.915E+000
1.514E+001	8.364E+000
1.694E+001	1.116E+001
1.810E+001	1.289E+001
1.829E+001	1.297E+001
1.861E+001	1.261E+001
1.912E+001	1.068E+001
1.945E+001	1.050E+001
1.983E+001	1.042E+001
2.015E+001	1.007E+001
2.092E+001	9.025E+000
2.144E+001	8.847E+000
2.182E+001	8.542E+000
2.260E+001	7.017E+000
2.362E+001	4.093E+000
2.427E+001	3.051E+000
2.472E+001	2.797E+000
2.562E+001	2.669E+000
2.722E+001	2.568E+000
3.494E+001	2.542E+000